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* **Registration : 08:00 ~ 16:00 (BASTILLE ROOM, 3F)**
Hologram Exhibition : 13:00 ~ 16:00 (BASTILLE ROOM, 3F)

Tuesday, June 27 #1

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09:30 ~ 10:00	Coffee Break
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11:20 ~ 13:30	Lunch

* Registration & Hologram Exhibition : 08:00 ~ 16:00 (BASTILLE ROOM, 3F)

Tuesday, June 27 #2

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Chair : Leehwan Hwang (Kwangwoon University)

Time	Events
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14:30 ~ 14:50	**Coherently breaking rules for light's sake: a condensation of a few decades recording argon lit dcg** Michael E Crawford (Light Foundry)
14:50 ~ 15:10	**Making holograms with IPhone** Alaric Hamacher (Kwangwoon University)
15:10 ~ 15:30	**The 'Real/Virtual' exhibition of holograms at Gallery 286: Exploring the use of display holography in contemporary artistic expression** Sydney J. Koke (The Jonathan Ross Hologram Collection)

*** Registration & Hologram Exhibition : 08:00 ~ 16:00 (BASTILLE ROOM, 3F)**

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Chair : Leehwan Hwang (Kwangwoon University)

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* Registration & Hologram Exhibition : 08:00 ~ 16:00 (BASTILLE ROOM, 3F)

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Thursday, June 29 #2

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Chair : Leehwan Hwang (Kwangwoon University)

Time	Events
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*** Registration & Hologram Exhibition : 08:00 ~ 16:00 (BASTILLE ROOM, 3F)**

Friday, June 30 #1

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Chair : Philippe Gentet (Kwangwoon University)

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08:30 ~ 08:50	A large-scale pulse laser holography camera built with 3D printing and surplus optics John Holdsworth (Newcastle University), Martina Mrongovius (Lake Macquarie City Council), Matthew Willis (Newcastle MWConsultancy)
08:50 ~ 09:10	Synthesis art and other applications of DCG holograms in display holography Michael Shevtsov (S. I. Vavilov State Optical Institute)
09:10 ~ 09:30	Holography, serendipity & me: the ups and downs of 75 years Ian Lancaster (Lancaster Consulting)
09:30 ~ 10:00	Coffee Break
10:00 ~ 10:20	A call to arms: margaret benyon's antiwar holograms Zsofi Valyi-Nagy (The Center for Advanced Study in the Visual Arts)
10:20 ~ 10:40	Efficient production of holograms for hands-on holography course Emanuel Istrate (Toronto University)
10:40 ~ 11:00	Art and new media: visual information recording for digital art holograms in higher education context Maria Isabel Azevedo (Aveiro University), Nuno Chuva Vasco (Coimbra Education School)
11:00 ~ 11:20	My journey from color holography to pulsed portrait, holographic printing and lenticular lens 3d display Yuan Quan (3D Holo Art Laboratory)
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* Registration & Hologram Exhibition : 08:00 ~ 16:00 (BASTILLE ROOM, 3F)

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Chair : Soonchul Kwon (Kwangwoon University)

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14:20 ~ 14:40	Teaching hands-on the science and art of holography Emanuel Istrate (Toronto University, Victoria College), Michael Page (OCAD University)
14:40 ~ 15:00	The contributions by nils abramson to the field of holography Jonny Gustafsson (Royal Institute of Technology)
15:00 ~ 15:20	Holographic reconstruction of 360° nadar's revolving self portrait Philippe Gentet (Kwangwoon University)
15:20 ~ 15:40	Preserving display holography: what to keep, where, and why? Pearl V. John, India Cook (Southampton University, De Montfort University)
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* Registration & Hologram Exhibition : 08:00 ~ 16:00 (BASTILLE ROOM, 3F)

Saturday, July 1

Social Program (DMZ, Demilitarized Zone)

Time	Classification
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~ 10:00	Arrival at Imjingak Pavilion Tourist Information Center
~ 10:30	Arrival at the southern end of Unification Bridge
10:40 ~ 11:40	The 3rd Tunnel Tour
11:50 ~ 12:30	Dora Observatory Tour
~ 12:50	Arrival at Unification Village Direct Sales Office
13:00 ~ 14:00	Lunch
~ 15:30	Return to Sofitel

INTRODUCTION

Professor Tung H. Jeong decided to invite holographers to the first International Symposium on Display Holography in 1982. It took place in the summer at Lake Forrest College in Illinois, USA. This was the first international event where artists, amateurs, scientists, entrepreneurs, and commercial company participants, all in Display Holography, met for one week. There we met Emmett Leith, Stephen Benton, and Nick Phillips and artists like Margaret Benyon, John Kaufman, and Setsuko Ishii among many more. This was a very successful symposium, and it created an interest in attending the next one at Lake Forest College, three years later. At the Lake Forest ISDH event in 1991, Yuri Denisyuk who was allowed to travel outside Russia, decided to attend and present a paper. These ISDH events continued at Lake Forest College until summer 1997 with many returning and new international participants.

I organised the first symposium outside USA, which was the 7th ISDH at OpTIC Technium in Wales, UK. After that, we have been in China, Russia, Portugal and once back in the USA at MIT.

This year, after a long delay caused by the pandemic, we have finally been able to get back together, this time in Seoul, South Korea, thanks to Professor Seung Hyun Lee. I hope it will be a successful event with both old ISDH participants as well as new ones interested in Display Holography.

Hans I. Bjelkhagen
Co-Chairman

Welcome to the 12th ISDH in Seoul, Korea. Around 60 papers and over 50 holograms have been submitted to this symposium. This year, we can see that the flow of display holography is moving predominantly towards holograms using digital printing technology.

I would like to thank Philippe Gentet for organizing a hologram contest using CHIMERA printing technology. An exhibition of the participants' work will be held during the symposium.

I would also like to thank Filipe Alves and Yves Gentet for creating and organizing a Lippmann photography workshop. Finally, I would like to thank Hans Bjelkhagen, Stas Zacharovas, Michael Page, Filipe Alves and Yves Gentet for their participation as invited Speakers. Dr. Hans' experience has been very helpful in preparing for this event, thank you.

Seung Hyun Lee
Co-Chairman

TRACK 1.

Art Concepts and Techniques

Promoting holographic art
―Report on solo exhibition ―

Setsuko Ishii
1-2-3-513, Kohinata, Bunkyo-ku, Tokyo,112-0006, JAPAN

ABSTRACT

This paper reports on a solo exhibition of my artwork that was held at Kitakyushu Municipal museum of art in Japan in 2022. It has been 40 years since I began using holography as an art medium. Such an opportunity called for the editing of the catalogue raisonné of my own work. It was found via the catalogue that over130 artworks have been produced over the past 40 years. Of these, 30 artworks, including the first and latest holograms, were selected and laid out in two exhibition rooms in loose chronological order. The total floor area of the two rooms was 1000sqm. Most of my works are installation, sculpture, and wall-hanging-type flat works. They were combined with holograms and other materials. We worked hard, as usual, to set up the holograms and lighting, especially the installation works in the space of the museum. This type of a medium offers several attractive characteristics. In the exhibition, viewers encounter various artworks that utilize different attractive hologram features. This paper describes the possibility of holography as an art medium through the artworks in the exhibition and demonstrates ways in which to set up holograms in an authentic public museum of art.

Keywords: Art in Holography, solo exhibition, art medium, catalogue raisonné, installation, sculpture, wall hand type flat work, museum of art

1. INTRODUCTION

1.1 The concept of the exhibition

This exhibition was realized after a preparatory period of six years. We spent considerable time to organize the documents regarding my art activities for 40 years and to checked the condition of each artwork, from the earliest to the latest ones as much as possible. When the museum informed me that they intended to organize a big solo exhibition of my artworks at their art museum, they began by explaining the meaning of this exhibition. Currently, most people are not familiar with holography as an art medium. This exhibition would be a means for spreading this innovative artform. Additionally, documenting these works for posterity is crucial.

While the artist is alive and able, the museum endeavors to document the holographic works and artistic activities of each artist, in addition to checking and listing all artworks. The curator informed me that that was an appropriate time to do so, otherwise, holographic art would be forgotten in art history, and no artist would be able to exhibit such works in future. Holding the exhibition at the art museum would be the perfect opportunity to introduce holographic art to ordinary people in a fitting environment and educate museum staff about holographic art and the method of installing them. This implies handling holographic art for the next generation.

During my activities in the field of holography art for 40 years, I faced many difficulties. For example, setting up holographic works in a gallery or art museum is challenging and complicated compared with assembling paintings or sculptures. It is difficult to find a place to display holographic works. It is more important to watch a real hologram and experience the holographic environment than to watch a photo or video. Such is the nature of the holographic medium. When I want to announce about exhibition widely, I am always frustrated about leaflets. Photo and video cannot convey holography work enough. For people who don't know about holography, it is not easy to imagine and interest holography. Because the holographic features cannot be transferred to any other mediums, for example, photo or video. I was always in a dilemma about this matter. For setting up holography works, I always attended in prder to make sure the correct lighting angle for holograms and set the installation works by myself.

I appreciate the museum's offer. The title of the exhibition was "Art in Holography: Pioneer - ISHII Setsuko," at the Kitakyushu Municipal Museum of Art, from July 16 to September 6, 2022. The poster is shown in Fig. 1.

1.2 Editing raisonné

All of my holographic works and artistic activities are written down in the catalogue raisonné (Fig. 2). Primary materials are required to ensure accuracy. It was difficult to find the suitable works to be catalogued from the pile of old material. To print photographs of the exhibition in the catalogue, we had to finish setting up all the artworks one month before opening the exhibition. It was the first time that I had experienced such a luxury of space as well as visibility and promotion of my works.

It was hard work to check the condition of the holograms stored in the warehouse for a long time. Great efforts had to be taken to preserve and revive the holograms from long ago. Some of the early holograms (silver–haloid film ones) were damaged and their images had disappeared completely. There were two different cases where damage was observed: In one lot(created in 1990), only one film was damaged and lost its image, whereas all other holograms seemed intact. The holograms were sandwiched between two acrylic plates. In the second case, all holograms in the same lot(created in 1989) completely lost their images. One of the holograms in the second case was displayed at an exhibition in 2014. At the time, the hologram appeared to be fine. After eight years, I discovered this hologram, which was rolled and kept in the tube and lost its image. Subsequently, the damage to all the holograms in the same lot, which were sandwiched between two acrylic plates was observed, with their images lost altogether. In both cases, the film maker as well as chemical processes employed for their creation were different. It is yet unclear to me why only these holograms were seriously damaged.

Since 1990, I have created several large-format film holograms. To exhibit these properties, most films were sandwiched between acrylic plates. However, it was difficult to keep the films flat under these conditions in the warehouse. Some of the holograms were not available for display because the film rippled and the holographic images were distorted; I discovered however, that if the film is laminated between two pieces of glass, this problem will be resolved, and this would be the best way to protect the gelatin and maintain the hologram film in good condition. I have already completed some of my work. However, large laminated glass holograms are very heavy and difficult to handle during shipping and setup. Future research should focus on how to protect the gelatin and keep the film flat. The films that were rolled and kept in the tubes were in the best condition regardless of whether they were old or new, except for the one previously mentioned.

Finally, I discovered through this sorting and cataloging that I have created over 130 artworks in 40 years. I had not calculated this until then.

The next step was to select the works for the exhibition.

Fig.1 The Poster of the exhibition: B2size

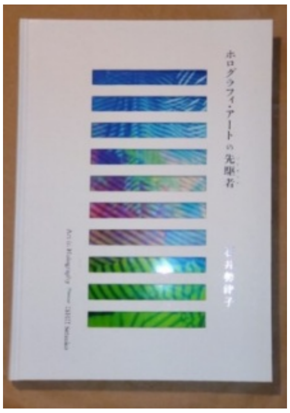


Fig. 2 Catalogue raisonné

2. THE EXHIBITION

The Kitakyusyu Munisipal Museum of Art, where the exhibition was held, was designed by Arata Isozaki and completed in 1974 (Fig. 3); it comprises modern and contemporary art works by domestic and foreign artists. This museum is renowned for its exhibitions of collected works and special exhibitions.

The Museum is located on top of a small hill in a park with abundant greenery. Outdoor installation works and the Appolonian Gift series were set in front of the museum.(Fig.3). All visitors were exposed to this installation before entering the museum. This installation was composed of several hologram grating objects formed with a bent polycarbonate plate. The hologram grating diffracts sunlight and grating objects radiant with brilliant colors under the sun. Color changes according to the sun’s movement and from different viewpoints. The image in the poster is a document of the installation work at the ancient Roma ruin villa dei Quintili (2007). A total of 300 objects were installed on the slope. The highway runs on the side, and the car drivers definitely observed brilliant colors on the green slope from far away.

Fig. 3. Outdoor installation-

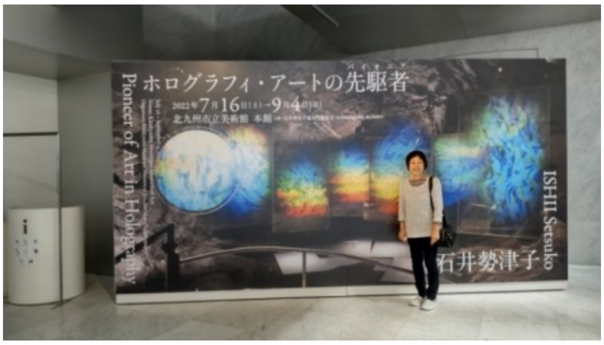


Fig. 4. Exhibition panel in the entrance hall

3. THE FIRST EXHIBITION ROOM

The exhibition space consists of two rooms. The total floor area is approximately 1,000meter square, where 30 artworks were exhibited, from among the 130 works across 40 years.Fig.4 shows the exhibition panel in the entrance hall of the museum. The image was the emblem of the exhibition at the Retretti Art Center in Finland(1994), which was located underground space where was dug the granite bed rock for this art center and wild surface was uncovered.

In the first room of the museum (Fig. 5), early works(Fig. 6-Fig. 10) were exhibited from the first holographic works(Fig. 6); These images reveal how I unfold holography. It was my first experience witnessing the method of exhibiting works in this museum, which involved exhibiting the works without title and caption, or any information accompanying the works. When I noticed this matter, I made inquiries, because the titles and works form a complete, inseparable set. Sometimes the title has a profound meaning, without which, the work itself may not be adequately interpreted. I asked the curator about these matters, and their explanation was as follows: In the case of this exhibition, it was a good idea to display the works without titles or captions. Because most visitors were not familiar with holography, they might look at holograms for the first time, and the museum’s focus this time, is that people concentrate on watching holographic works and experience new perceptions without any preconceptions believed that would interfere with the observing of themselves. Finally, I accepted this idea.

When people move from the first exhibition room to the second one, they walk through a small space for rest, while in the leaflet, the floor map of the layout of artworks and their titles were available; if someone was interested in more detailed information about the works, they could return to the exhibition room and be able to know the title of the work. I saw several people watching work with a leaflet in their hand.

3.1 Contrast holographic image and the real object

The first holography art work was “The process of birth”(Fig.6) (1978). The theme was a contrast holographic image of real eggs, and a reflected image on an acrylic plate. We can see that the holographic image exists in real space and occupies real three dimensional space, but we cannot hold them in the hand. When the holograms are shown with together these materials, the new experience in the perception of holography would be more emphasized than that hologram itself.

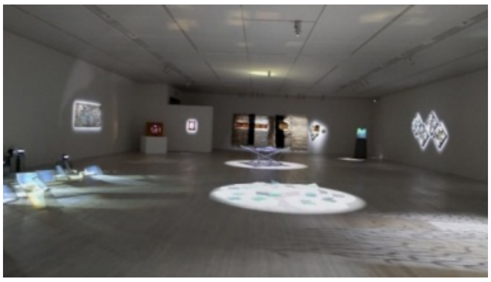
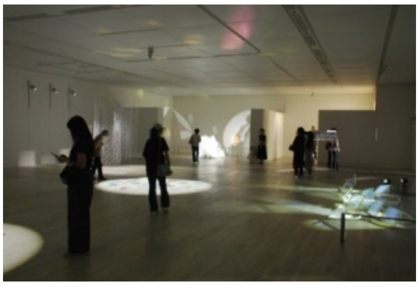



Fig. 5 The scene in the first exhibition room

Fig. 6 Process of Birth 1978 rainbow hologram

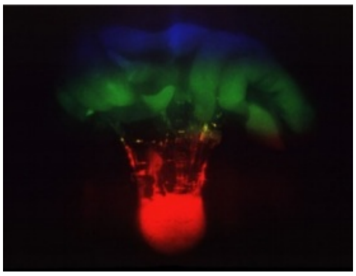


Fig.7 Crystal White 1979

Fig. 8 Self-portrait 1995

Fig. 9.Papillon blue 1985

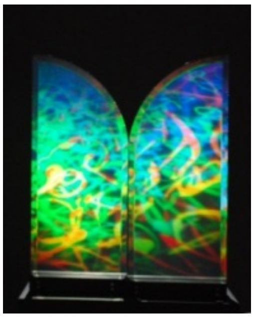


Fig. 10 Photon Drawing 1997

3.2 Installation work

An image of a rainbow transmission hologram has a limited viewing angle. The color and shape of the image change according to the moving viewpoint. Outside the limited viewing angle, the images disappear. This is a unique feature of holography. The installation work that combined the rainbow hologram and cotton net was titled “Sequential blank” (Fig. 11). “Work N” (Fig. 12) is installed on the floor, where the holographic image tube overlaps the real plastic tube. In Both installation works, viewers are required to walk around the work and look for the images actively. Otherwise, the viewers may miss this .information. The holographic image has its own address in the space, and the viewer can face the images only when they stand in the correct position in the space, which I had created at the Museum of Holography in New York as an artist in residence.

The next image is the installation work on the floor, which contains small white marble and DCG reflection holograms whose features have a very realistic image. Putting a dent shaped hologram on the floor lends the impression that the floor may be dented. This installation invites the viewer to have a new visual experience. We notice that we are very sensitive about the unevenness of horizontal planes compared with vertical ones. These works traveled abroad many more times than I have done. Each time, only the holograms were sent from Japan, while the other materials were required to be prepared onsite. “Hide and Seek” (1984) (Fig. 14) presents an installation with a DCG reflection hologram, chicken wire, and quilt padding. In this image, a colorful shadow appears on the wall. When a visitor enters the installation area, the visitor’s shadow appears on the wall. The hologram images show broken glass chunks with sharp edges. I am interested in contrasting the different textures: sharp, soft, warm, cold, and hard.

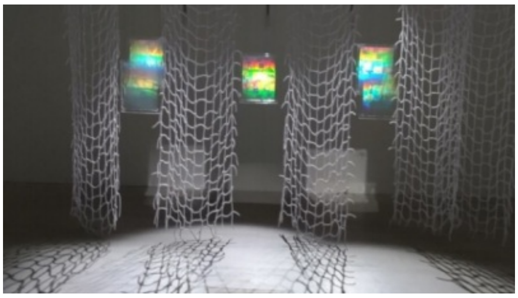
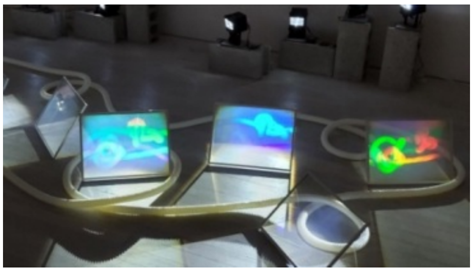


Fig.11 Sequential Blank 1985 Multicolor rainbow hologram ,Cotton net



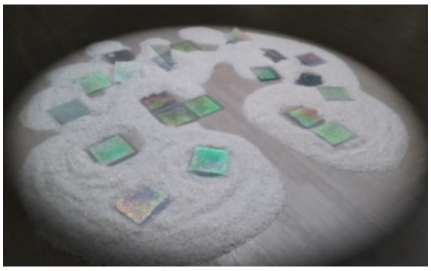
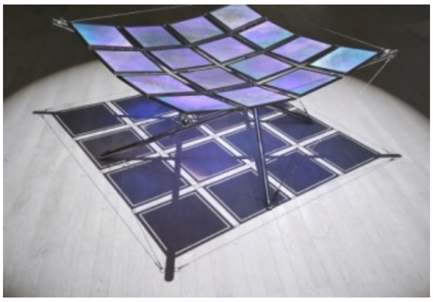


Fig.12.Work N 1981 two color rainbow hologram Fig.13 Riverside 1983, DCG reflection hologram

Fig 14. Hide and Seek 1984 DCG reflection hologram, Chicken wire, Quilt padding

3.3 Sculptural work

“Pseudo Plane,” (Fig. 15-a) is an objective work consisting of 16 DCG holograms that are connected to each other (Fig. 15-b)and a tension structure made of stainless steel. The four corners of the flexible hologram plane are hung by the tension structure support. The center holograms have a floating image, and the corner ones have a dent image as they modify the view of the flat ground.



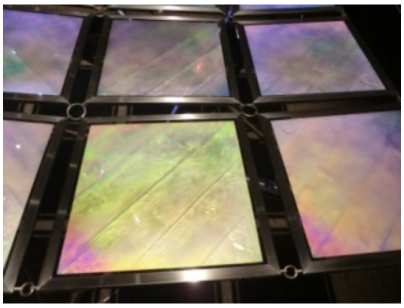


Fig. 15-a. Pseudo plane 1981, DCG reflection hologram, stainless steel Fig. 15-b. details of the Pseudo plane

3.4 Wall-hanging--type works

‘Visible Temperature α’1987, （Fig. 16） composed s holograms (silver haloid reflection type)and various material, such as wool, jute, cotton, steel mesh, and mettle nails. The images of holograms were recorded feather and lumps of wool., which were very realistic and as floating on a glass surface. If one attempts to grasp this the holographic image in the air, one may misunderstand the image to be real, and feel warm and gentle texture. When one sees the wire net, one may not recognize it as a hard material. I am very happy if the viewer has a new experience in the perception of this work.

Fig.16 Visible temperature α 1987, silver-haloid reflection hologram,

Plant shape is an attractive subject for hologram images, and images from nature are always comforting. The images of the following four artworks (Fig. 17-Fig. 20) are silhouettes of grass plant and tree branches. “Memory of U” 1999 (Fig. 17) and ‘Memory of U Ⅱ” 1997 (Fig. 18) are both DCG two-color reflection holograms. Their images exist between glass surfaces. The background of the hologram is painted black and white. Some images can be observed behind the background drawings. I would like people to enjoy the beautiful colors that change according to the moving viewpoint and these images which have uncertain depth.

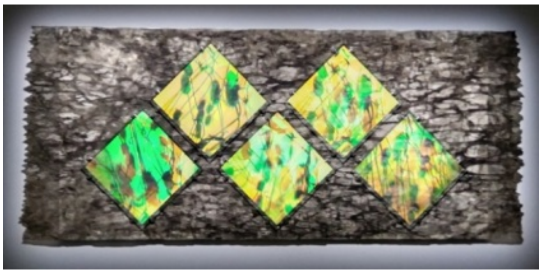


Fig.17. Memory of U 1999 DCG hologram

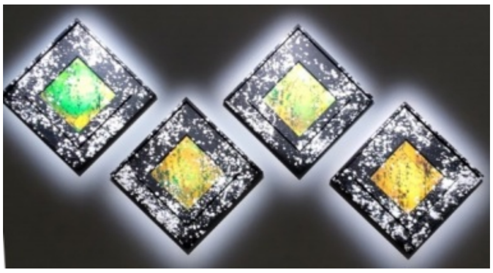


Fig. 18 Memory of U II 1997, DCG hologram

Fig.19 Another Window 1995 Silver-haloid reflection hologram

Fig. 20. Invisible window 1992

“Another Window” 1995 (Fig. 19) and “Invisible window” 1992 (Fig. 20) are silver haloid reflection holograms, which were assembled into four film holograms, 80 cm×80 cm each, into one image. “Another Window” (Fig. 19) was laminated between two pieces of glass, and “Invisible window” (Fig. 20)was only sandwiched between two pieces of glass. The film of Fig. 20 rippled slightly, and the image got slightly distorted.

４． THE SECOND EXHIBITION ROOM

In the second exhibition room, the second half of my works were, which comprised large-format multicolor rainbow holograms. To set the transmission hologram, a large space behind the hologram is required because of the lighting. People stand and move to change their viewpoints in front of the works .When we lay out the positions of the holograms on the floor map, we must first consider the flow line. However, it was not easy to adjust to these conditions. I was hoping to display more works, however, the museum advised me to reduce the number. Finally, 17 works were exhibited in the second room. After completing the setting work, I realized that reduced number of works created a comfortable space for watching the works. Therefore, it is important to provide comfortable spaces for visitors.

Until this time, large-format rainbow holograms were hung from the ceiling; however, we had to think of another way to represent them. Some of the holograms were located at the base. For some large installations, special spaces were created by assembling an aluminum truss in a second room. Holograms could be hung from the top. However, we could not observe the entire room. Visitors watched the works individually along a flowline. Near the entrance of the second room, sufficiently bright holograms were set up because of the bright light coming from outside and the bright environment.

4.1 Photon drawing series- brush stroke

“Distorted air” (Fig. 21) was the first hologram whose image was created with a brush stroke. I started using this method when I was involved in an exhibition named “Homage von Gogh,” which commemorated the centennial of his death in 1990 in Tokyo. The exhibition focused on five artists to create new works, keeping in mind the theme of the exhibition, each of whom selected a different medium, namely video, sound interactive, kinetic, environmental installation, and holography. I followed an Impressionist idea with a lot of thought; I attempted to realize this idea with holography, dynamic brushstrokes, and brilliant colors, and expressed it using light. The result of this effort was “Distorted Air,” 1990 (Fig. 21). I attempted to paint in the space as a canvas, using holography as a brush and light as a pigment. The image of the hologram I tested was a landscape and an outdoor scene. The multicolor rainbow hologram changes its color continuously according to the moving viewpoint. One can find a scene of sunset, grassland, twilight, snowfield, or flower garden in the spring, depending on your vantage point. I am a great admirer of this form. Simultaneously, I created “Under the water” (Fig. 22).

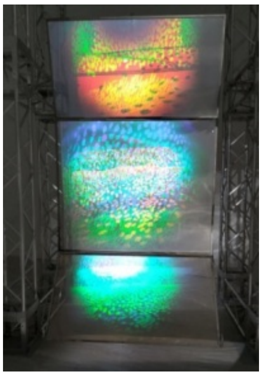


Fig.21 Distorted Air 1990

Fig. 22 Under the Water 1990

s.

4.2 The brush stroke and real plants

The large installation “Grassland to the Sea” 1992 (Fig. 23) was one set and the images were a combination of brushstrokes and silhouettes of real plants. I am still interested in shapes in nature.

“Fragment of Nature- Landscape” (2017) is a multicolor rainbow hologram. These were installed on walls. The Film hologram was laminated between two pieces of glass, and set with a mirror behind the hologram, Therefore, the rainbow hologram was converted to a reflection-type image. Reflection images are much easier to set up in everyday life spaces. .

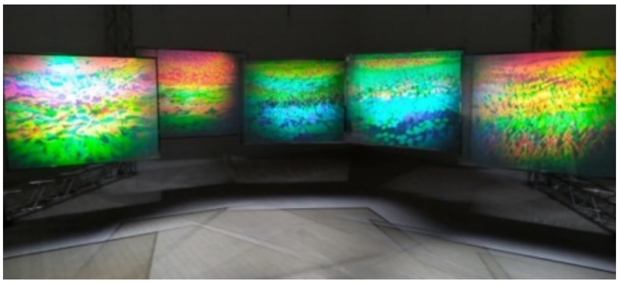


Fig 23 From the grassland to the sea 1992, multicolor rainbow hologram

Fig 24. Fragment of Nature- Landscape 2017 Multicolor rainbow hologram with mirror

4.3 Light and WaterText

The installation works with the effect of water, “The Murmur of Aqueus” (Fig. 24) is composed of seven different holograms (Fig. 26) and water ripples appear in the holographic images. Behind hologram (Fig. 25),water vessels were placed on the floor in which the water and mirror. Devices that dropping water in the vessel were,hung from the top. Light was reflected on the mirror which sank under water, and illuminated the hologram.

Fig. 24 The Murmur of Aqueus (part of the image) 1994

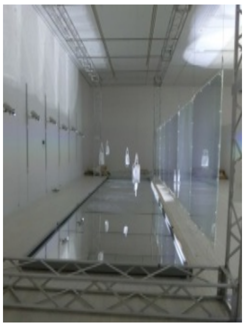


Fig. 25 Behind the hologram

Fig.26. Seven different images of the Murmur of Aqueus

The first installation of this work was shown in the exhibition at the underground art Center in Finland; this was the photographic document on the large panel in the entrance Hall (Fig. 4) I made several such installations combined with the water effect.

4.4 Frozen time -Pulsed hologram

The first pulsed hologram I created was “Crystal White” 1979(Fig. 7). Subsequently, I did not have the opportunity to create them fora . The next pulsed hologram, whose pulsed master hologram I created at the Holo Center in a long island city in 2000 as an artist in residence.I made many plused master holograms there These master holograms were transferred to four final holograms, which were multicolor multichannel and more than 10 master images were recorded in one hologram each, four years later in another studio. Two of these were set up in the area near the entrance to the second room.Fig. 28 is the left side of Fig. 27, which shows a scene of scattering feathers in the air, while Fig. 29 is the right side of Fig 17, which shows a scene of popcorn scattering in the air. Both images are very bright.


Fig.27 Entrance scene

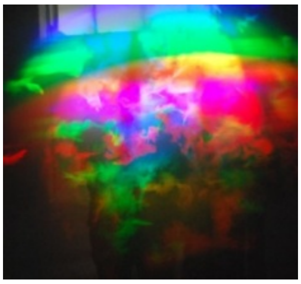


Fig.28.left image of Fig.27

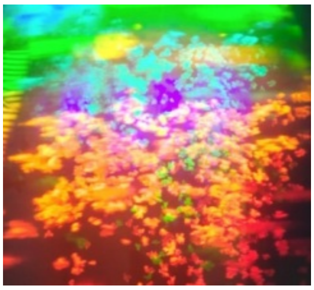


Fig. 29. Right image of Fig.27

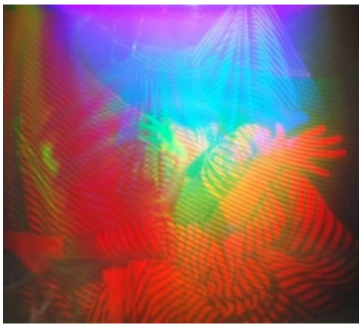


Fig.30.Self-portrai Bogy with Fabric A 2002

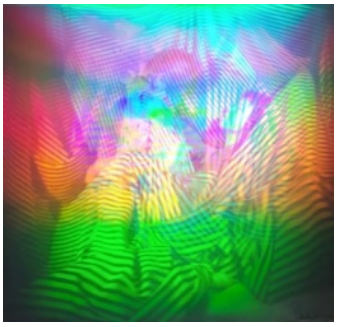


Fig.31 Self-portrait Body with Fabric B 2002

The image of rest two holograms were “Body with Fabric A” (Fig, 30) and “Body with Fabric B”(Fig.31), each size was 110cm×130 ㎝ each.The form of the body attracts artists who live in all times and places. I tried to create these images too..

Latest opportunity to make pulsed hologram was that I got a grant from Hologram Foundation in France in 2013, which offer to the artist to be able to make holograms at a pulse studio at Ohio State University.

I created many pulsed master holograms there. After that on my way back Japan, I went to second studio, Holographics North, in order to make final holograms, which located in Burlington VT state was able to make large format holograms. Concerning holographic work, we have to work several different studios to complete final hologram. Final hologram was ‘Self-portrait 2013’(Fig32) size was 85cm × 95cm which composed more than 12 different images of master holograms.

Most of my large-format holograms were made by Holographics North Inc. I had one more chance to return there, and the “Fragment of Nature- Landscape” 2017(Fig. 24) was the last hologram which was made at the studio. A few years later, Jon Perry who was owner of the studio announced that the studio had closed. This was disappointing news

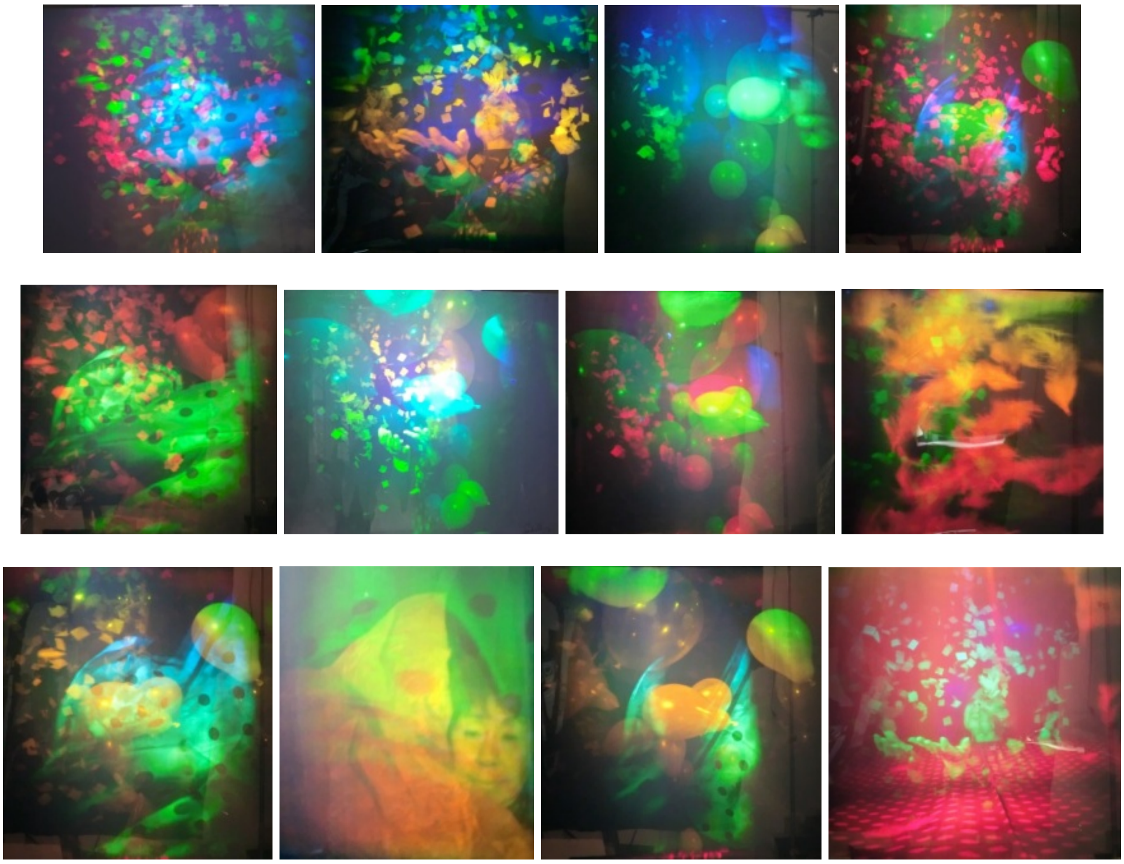


Fig. 2. Self-portrait 2013 Image variation according to different view points

4.5 CG animation hologramTables and captions

I had the opportunity to create animated CG holograms.(Fig. 33, Fig. 34). According to moving the viewpoint, round shape animate. All images of cell and ball are made using computer graphics by an engineer. I made a real model to represent a GC image. Floating （Fig. 34.）, all Images of three masters were made from CG; however, the images oft, "Floating Cell" (Fig. 33) (left) and "Floating Ball" (Fig. 33) (right), were mixed with the CG and analog images.

Fig. 33 Floating-Cell(left) Floating –Ball (right) 1997   Fig. 34 Floating II1997

4.6 Environmental installation

Installation "{Light in light" (Fig. 35) comprised DCG holograms and dichroic mirror glass.

Colored shadow and colored reflected light appear on the wall and floor（Fig. 36）.
Visiters were allowed to take pictures and video freely in the exhibition room. They enjoyed walking into this installation and take pictures

Fig.35 Light in Light 1989, DCG hologram, dichroic mirror glass

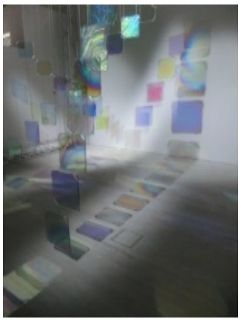


Fig 36 reflection on the floor and wall

5. CONCLUSION

I would like the viewers to weave new experiences and encounter their own inner selves by viewing the space in the works I have created in this exhibition. It seemed that many young visitors came in spite of coronavirus situations. I heard from museum staff that usually, the number of the visitors to the contemporary art exhibition was less than that of modern art exhibition. But this time, many visitors came to our exhibition, it was unusual. I was very pleased to hear this news and I would like to express my deepest appreciation to everyone concerned for their assistance in the realization of this exhibition.

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Digital art hologram of a sea explorer: a poetic view

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ABSTRACT

During the Age of Discovery, Portugal extended its reach to the Far East and opened maritime trade between East and West. Vasco da Gama was the first navigator to travel from Europe to the Southern Hemisphere, including India, China, Japan and Macau, a feat that many considered impossible at the time. Navigators did not believe that the Atlantic Ocean and the Indian Ocean were connected. However, due to this feat, there are reports that Portugal's first encounter with Korea was in 1577 and later in 1604.
This artwork is homage to the Portuguese navigator who made possible the connection between the Atlantic Ocean and the Indian Ocean. In fact, Portugal was at the forefront of European exploration between the 15th and 16th centuries, writing books on western astronomy and also on geography, drawing maps, inventing and developing several scientific instruments to the navigation.
In this paper I'm presenting and discussing the artistic concepts and the movie created about the Portuguese navigator, as a sea explorer. The character in the holographic image is calculating the inclination of the Sun relative to the horizon or the distance between the holographic image and the viewer?
This movie is the visual information for printing digital hologram according to the CHIMERA™ half-parallax video captures instructions. Thanks to the opportunity of the ISDH 2023 Contest, this movie was created and submitted, with the aim of having it printed by CHIMERA™, in case it's selected.

Keywords: Digital Art Hologram, holographic image, AI, movement, interaction

1. INTRODUCTION

In this paper, the creative process and experimental techniques of digital holographic image are analysed from the point of view of visual arts. In a symbolic way I will speak briefly about the Great Portuguese Discoveries that led to the success of Vasco da Gama's navigation opening the Cape route directly to Asia. Captain Domingos Monteiro arrived in Korea in 1577 and there are records that João Mendes later arrived in 1604. As Portugal was a pioneering country in the era of the Great Discoveries, it is not surprising that where Portuguese the first Westerners to reach the Korean Peninsula.

My art research has been about the aesthetics of light, as an entity in itself, and how the viewer interacts with it; holography is one of the media that I have used in this process. In the new era of holographic image and the creation of digital holograms, imaging systems are being developed to capture dimensional content and also possible software to edit it. Since 2010, I have been developing a series of digital art holograms that has been showed in international conferences as well as in international artistic context. Exploring the movement inside and outside the holographic space making the physical space of the viewer also part of the work, and proposing a new type of performance art. It is the viewer's movement that will direct the performance, which was recorded on the holographic plate. The bodily experience of interaction with the holographic image is fundamental it is the time of the image symbiotically activated with the participant that creates the total performance.[1]

2. A SEA EXPLORER: A POETIC VIEW

Vasco da Gama opened the direct Cape route to Asia and showed that it was possible to reach India by sea, arriving in Calicut in 1498. It was the realization of an old dream: contact between West and East no longer depended on the Silk Road and promised a great income to the Portuguese Crown, with the spice trade to be a major engine of the world economy from the end of the Middle Ages to modern times.

It was on the “Caravelas” that the Portuguese learned to navigate, the success of the two-masted “Caravela” was due to its extraordinary sailing qualities, which were the result of a large sail surface, combined with a long, slender hull that made it fast and easy to manoeuvre. “Caravelas” were replaced by “Naus” on trips to the East, but they continued to be used in Atlantic navigation until the 18th century.

Nautical science already dated back to the 13th century, but Portuguese expansion forced a very rapid evolution, since it became necessary to overcome new obstacles, with research and evolution being the responsibility of an elite of astronomers, pilots, mathematicians and cartographers. In fact, Portugal was at the forefront of European exploration between the 15th and 16th centuries, writing books on western astronomy and also on geography, drawing maps, inventing and developing various scientific instruments for navigation, thus resulting from the developments of Portuguese nautical science.[2]

Portuguese navigators contributed to a new way of conceiving the world, but at the same time they had an enormous fear of the sea, caused by the stories that were told about what would exist beyond the known world, such as, for example, sea monsters that they swallowed the boats, and the voyages were subject to storms, with the crews always vulnerable to disease, suffering and death.[3]

It was these ideas, the fantastic and the mythical, the fear of the unknowing and the development of science that led me to the creation of image information, in the context of digital art holograms. Also reflecting on the scientific production of Portuguese navigation considered advanced at that time, relating it to the contemporary production of artificial intelligence that today we consider as the most technologically advanced way to “navigate” while questioning our humanity. As Professor Daviel C. Dennett says, “AI has not yet solved any of our ancient riddles about the mind, but it has provided us with new ways of disciplining and extending philosophical imagination that we have only begun to exploit”.[4]

3. CONSIDERATIONS ABOUT HOLOGRAM AND HOLOGRAPHIC IMAGE

Holography can be considered part of the light recording media, such as photography, video or film. On the other hand, the holographic image can be placed in the tradition of light in the visual arts, as it is able to offer a unique interpretation of the combination of light, space and time.

In the photographic process the light source can be natural or artificial; however, in analogue holography, the light must be coherent and, therefore, it is necessary to use laser light. This condition is essential in the creation phase of the analogue hologram. In digital holography[5, 6], the use of the laser is not necessary during the creation phase, because the images are mainly recorded from a variety of video recordings, Cinema 4D, 3D Studio Max, 3D CAD programs, Maya, as well as 3D image scanners, and then printed using lasers. There are also image capture systems for producing holograms of living beings and landscapes, such as the HoloCam Portable Light System, which produces a digital photo/video sequence in the so-called HPO format (horizontal parallax only) for holographic printers Syn4Ds, from the Geola Digital uab, in Vilnius, Lithuania.[7]

For several years I made artworks in the studio at De Montfort University, in the Modern Holography Group, using this mechanism, creating image information for printing digital holograms at Geola Digital uab. The HoloCam Portable Light is described in its manual to be used in a specific manner, in relation to the space and scenes to record visual information. Despite that, we used it in several different ways to explore and develop the utilization of this device, developing the use of the medium in order to realize the artistic concepts. To create that kind of images, we prepared the studio and setup for the visual information, studying the construction of the image for each hologram, having in mind that in the end the observer will see 3D images in a dynamic space, more exactly 4D images. Every movement needed to be slowly choreographed, otherwise the digital holographic image will lose its 3D character and it will show up defocused. The light has to be adjusted in intensity and colour, having in consideration that the digital printing has a tendency to be darker. Many of these images have a series of layers, each layer being a different recording of a performance. The recordings of the experimental performances in the studio were then edited through the programs, Motion and Final Cut Pro X, allowing placing several scenes within an image. These videos were then sent to GEOLA, in Vilnius, Lithuania, to be printed as digital holograms. The final digital holographic performances only exist after they are printed and placed in the exhibition space so that they can be activated by viewer/participant interaction.

I´m having a new opportunity creating image information to be printed on Chimera™. This is a 3D holographic printer patented by Yves Gentet, in Bordeaux, France[8] intended to produce the new generation of digital holograms. He also names the digital holograms produced there by the name Chimera™. The data comes from a 3D capture of a real object or from computer generated objects using 3D software (such as 3DSmax). This data is used to calculate a hologram that is printed pixel by pixel (called "hogels") using RGB lasers and holographic recording material known as Ultimate Uo4, also developed in this company. I tried to apply the experience I had from using the HoloCam in the studio, which is also a 3D capture, in which the camera moves on the rail in front of the scene; so we had more freedom to create the scenarios and develop the experimental performances. Now, working in the studio at the Centre for Informatics and Audio-visual Media, at the Education School of Coimbra, in Portugal, using the Chimera™ instructions for video capturing, where the scene rotates and the camera remains static, sounds more restrictive but is also a good challenge.

Holograms are always recorded on a holographic plate, whether created by analogue processes or using digital processes. I consider it is important to mention the difference between hologram and holographic image[9], the hologram is the glass or acetate plate registered and subsequently revealed (that is, after chemical processing as in analogue photography) and the holographic image, in 3D or 4D, appears only when the hologram is properly illuminated and the viewer is located in the parameters of the viewing zone. A hologram may or may not reconstruct the image that was recorded, depending on the lighting conditions and the position of the viewer. Holography should not be confused with stage illusions, such as Pepper's Ghost[10], which are also often incorrectly called holograms.

The production of digital holographic images comes from several artistic areas such as photography, film and video, after being mixed, electronically manipulated and digitally synthesized, offering visual effects and additional important resources for the artistic creation of images, which are different from analogue holography[11]. The expressive possibilities of the medium are increasingly and one of the main aesthetic features is time, which is orchestrated by the viewer.

4. CAPTURING IMAGE INFORMATION

In order to register the image information, which could be printed as digital reflection hologram, some performances were developed in one of the studios at the Centre for Informatics and Audio-visual Media, at the Education School of Coimbra, in Portugal, using the technique Chroma-Key.

According video capture instrucions[12] from Chimera™, the points of views of the scene was recorded on a 120° arc of circle, rotating the scene and keeping the camera static. The distance of the camera to the centre of the rotation was 1,10 meters; the camera was oriented vertically. According the instructions, the centre of the scene rotation will become the vertical axis of the final Chimera™. Anything of the scene in front of this centre will appear "floating" in front of the glass plate. We used the video format HD: 1080x1920 that is the recommended for 30x40 Chimera™ 500μm hogel print (cropped to 660x880).

The recordings of the experimental performances, in the studio, were then edited using the Motion and Final Cut Pro X programs, allowing placing several scenes within an image. When videos are printed as holograms, it is used the luminous information of the videos. The recording resumes the impression of an interference pattern calculated by a computer, carried out by a laser beam focused on the movement controlled by the same computer. After the registration and chemical processing of the emulsified plate, a reflection hologram is obtained containing the total amplitude and phase information of the interference pattern. The interference fringes that make up the hologram, when properly lit, produce a 4D image. The final performances only exist after the holographic printing, and after being placed in the exhibition space, because it is these digital holograms that allow these performances to be activated by the movement of the viewer/participant.

5. ART CONCEPTS AND IMAGE INFORMATION TO BE PRINTED

The evolution of navigation produced a revolution in thought. Navigators feared the sea, the contacts with oceanic hostility, in the middle of the 15th century, represented a beginning of a new era, characterized by a coexistence of new maritime techniques experimentation with the mythical imaginary linked to the ocean, giving way to curiosity and the desire to explore this unknown. Figures 1 and 2 are some maps with representations of this mythical imaginary.

Figure 1 - Sea monsters in the Madrid manuscript (1460) of Ptolemy's Geographia, National Library of Spain.

Figure 2- Atlas de Monte (1590), Library of the Archbishop's Seminary of Milan, Venegono Inferior (VA).

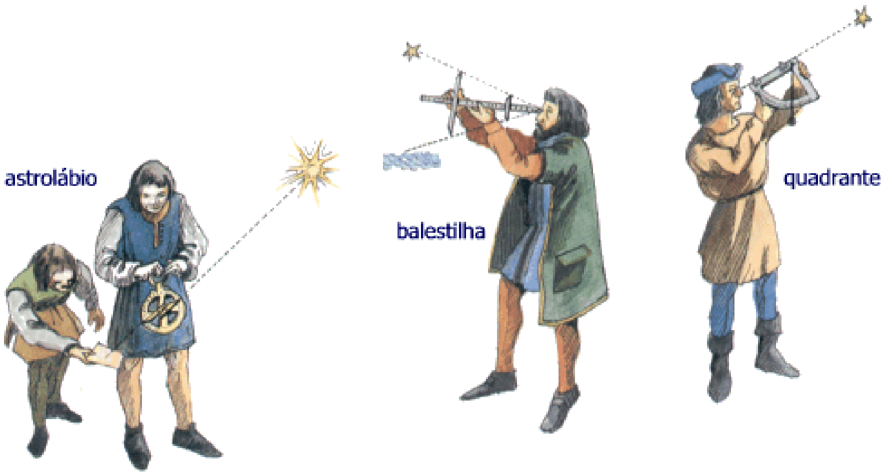

Figure 3- Nautical Instruments

The “octante” is an instrument for measuring latitude based on measuring the height of a star using two mirrors. It is the first instrument in the family of double-reflection instruments, much simpler and more rigorous than the “astrolábio, balestilha, quadrante” (Fig. 4), which introduced greater accuracy in measuring latitude. It was called “octante”, due to its shape of a 45º circular sector (that is, an eighth of a circle), allowing the measurement of angles up to 90º. The “sextante” (Fig. 4) was a development by extending the arc of the “octante” limb to 60º, whose purpose is to measure an angle between two objects. The instrument needs to be firmly held and aimed at the horizon through the “telescope”, in order to coincide the reflected image of the star with the image of the horizon aimed directly.

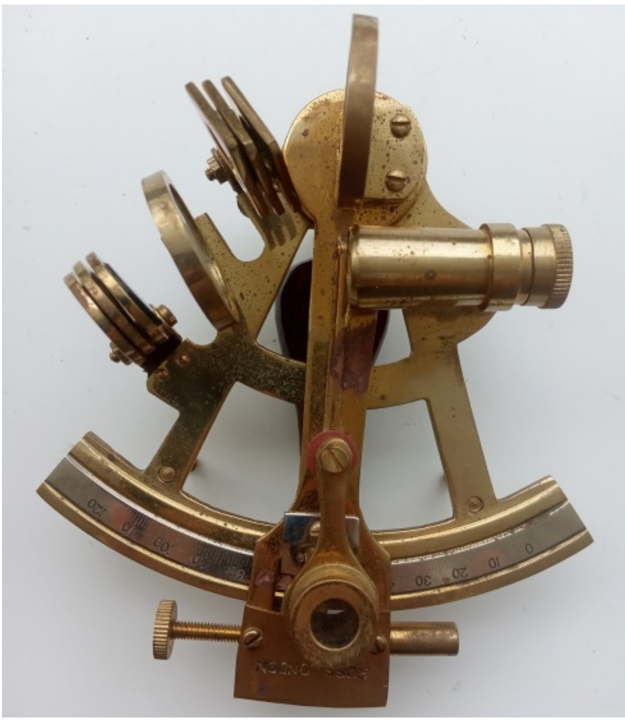

Figure 4. “Sextante”, from my collection.

The idea behind the making of "The Portuguese Navigator" was based on the fantastic and the mythical, and the developments of science to overcome the fear of the unknown. This artwork is a symbolical representation summarized in a single figure. Someone coming from the past who through the "sextante" seeks to our nowadays "position". According the viewer's interaction with the holographic image would be an encounter between the past and the present. Behind the figure are elements related to the sea and, at the same time, strange things, such as what is unknown, which can be both challenging and a true nightmare. This video is the image information to be printed as digital reflection hologram; some frames of the video are presented in Figure 5.

Figure 5 – The Portuguese Navigator, image information ready to be printed as digital reflection hologram

6. CONCLUSION

In the creation of art it is precisely through the unknown, hand in hand with the fantastic and the myth, that leads us to explore our ideas that will later emerge in the form of artwork.

I intended demonstrate through an artistic and poetic perspective the potential and versatility of Portuguese people through "The Portuguese Navigator". Portugal is a country with a millennial history that crosses various cultural layers sharing and reinforcing its past and present.

According my previous experience using the HoloCam in the studio, in which the camera moves on the rail in front of the scene, I had more freedom to create the scenarios and develop the experimental performances. Working now in the studio using the Chimera™ instructions for video capturing, where the scene rotates and the camera remains static, was more restricted and I needed to deal with the unknown in some way but was also a good challenge. Thanks to the opportunity of the ISDH 2023 Contest, this movie was created and submitted, with the aim of having it printed by CHIMERA™, if it's selected.

Acknowledgements

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A study on the art of bonsai within a holographic ideorealm

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ABSTRACT

Ancient Chinese literati longed for nature and integrated their perception of the mountain and forest into the art of bonsai. They employed plants and natural elements to shape ideal ideorealm. Light as a fundamental element inherent in nature, possessing the capacity to serve as a creator of holograms. Holography enables the reproduction of diverse entities and evocation of diverse imagery. After a brief background introduction, this paper elaborates on the ideorealm and contemplation of the landscape of life created by the series of bonsai works titled "Manifestation" that incorporates hologram.
Keywords: Holographic ideorealm, Holographic artwork, Bonsai art, Maple, Pine, Seed

1. INTRODUCTION

Ideorealm refers to the imagery system presented in lyrical works, where scenes and emotions intertwine, giving rise to aesthetic imagination. It is a term in Chinese used to describe the artistic realm formed by the integration of depicted life scenes and expressed thoughts and emotions in literary and artistic works. The characteristic of artistic conception lies in the fusion of emotions and scenes, where emotions are embedded within the scenes. Any art that moves and captivates the audience (readers or viewers) reflects not only the depicted “realm” but also the corresponding "intention" of the author. The author can express their state of mind through imagery and convey their emotions through it [1].

The concept of bonsai originated from the ancient Chinese philosophy of creation (Chinese art form of penjing “盆景”). In ancient China, the space of artistic creation was a means through which people conveyed their thoughts and spirits by creating physical objects [2]. The definition of objects in ancient China was broad and often linked to the way in which ancient people perceived the world. The art of creation was diverse and intricate, creating the living environment of ancient people and constructing a space in which viewers could traverse the macrocosm, mesocosm, and microcosm.

In Chinese cultural tradition, the popularity among the masses and the participation of literati transformed bonsai from a simple potted plant into a refined art form. This contributed to the improvement and development of the art of bonsai, elevating it to a humanistic medium, much like poetry, calligraphy, painting, and music. The art of bonsai has been handed down through generations [3].

Bonsai art condenses the beauty of nature, mountains, and ancient trees into a small pot, encompassing vast landscapes within one's grasp. It allows people to appreciate the beauty of natural scenery without leaving their homes. Compared to other art forms, bonsai exudes a natural vitality and aesthetic essence that captivates people and satisfy their aesthetic needs. Some works of bonsai art in China express the fusion of self-nature and thoughts and emotions, embodying the philosophy of “Harmony of Man and Nature” and “Unity of Objection and Man” [4].

Bonsai, as an art form that encapsulates nature, accommodates the universe and the world within a limited space. It also encompasses the human spiritual world, enabling people to transcend the mundane and achieve a state of "being in the world but not of it" [5].

Hologram, as a medium for capturing spatial information, creates an environment that combines reality and virtuality through changes in light. It expands and presents space in a three-dimensional manner, breaking away from the traditional narrative approach of art and constructing multidimensional narratives and meanings. It provides viewers with a richer sensory experience. The sensory experience of holography attracts the audience's attention, enhances their engagement, and facilitates deeper understanding and memory of the narrative content and meaning, thereby stimulating and expanding aesthetic imagination [6]. In this research, the author conducted numerous artistic experiments aiming to integrate various elements of nature using holograms, in order to create bonsai artworks with holographic ideorealm, thereby encouraging viewers to contemplate and experience.

2. ARTWORKS

The "Manifestation" series is a reinterpretation of plant bonsai artworks using hologram. The title "Manifestation" is derived from the combination of the Chinese character "显" (xian) and the natural landscape form. It conveys the meaning of manifestation and revelation under light. The "Manifestation" series consists of three experimental groups: "Maple Manifestation," "Pine Manifestation," and "Seed Manifestation."

2.1 Manifestation of Maple

Research has shown that even when a tree dies, it still possesses powerful vitality. The stored moisture in dead wood can provide sufficient energy for seedlings during dry seasons and create a warm haven for young plants in harsh climates, allowing them to thrive. Additionally, dead wood serves as a crucial part of the ecosystem, providing habitats for various organisms in the forest. It continuously sequesters and stores carbon for decades or even centuries, controlling the carbon dioxide content in the air and mitigating the greenhouse effect. Dead wood plays a decisive role in maintaining forest regeneration and the functioning of the Earth's ecosystem [7].

Ancient Chinese literatus Su Dongpo had a keen interest in the vitality of dead trees. In his work "Painting of Twisted Trees and Strange Rocks" (Figure 1), he depicted dead wood together with strange rocks, bamboo, and grass. The contorted and struggling posture of the dead wood portrays its boundless vitality, expressing reverence for the life force it contains. The renowned American photographer Edward Weston focused on dead wood through the manipulation of light in his photographs (Figure 2), conveying the unique charm of life possessed by dead wood through the interplay of light and shadow.

Figure 1. Su Dongpo's "Painting of Twisted Trees and Strange Rocks".

Figure 2. Edward Weston's photograph of dead wood.

Artwork "Maple Manifestation" (Figure 3) is based on a square bonsai container and showcases the maple tree, known for its seasonal changes. It depicts the state of the maple tree during the winter season, just before entering the next lifecycle. Above the branches of the maple tree, there is a thin holographic ring that intermittently appears and disappears under the illumination of light. This juxtaposition allows viewers to sense the hidden energy of these seemingly withered and dormant branches, which are actually harbouring the potential for a new awakening.

Figure 3.Maple Manifestation, 2023.

The holographic "circle" merges the ideorealm of greenery, life, energy, and cycles with the organic life form of the plant, creating a novel art form with distinct Chinese landscape aesthetics. Under the supply of light energy, the holographic imagery manifests, revitalizing the withered wood and creating a fusion of imagery, facilitating the integration of nature and artificial elements. The cyclical changes of natural life may appear disorderly, but behind them lies a certain order of development. In the case of this artwork, the maple tree that grows naturally harbours new life within its withered branches, where the process of renewal is taking place.

As viewers move in front of "Maple Manifestation," the holographic circle occasionally appears and disappears, requiring them to seize the limited opportunity to appreciate the scene. Multiple attempts to approach and observe the artwork may only be aimed at experiencing the imagery, even if the time available is fleeting. The viewers' behaviour seems to echo the logic of the tree's growth, which also requires them to grasp the limited suitable time within a year for photosynthesis [8] and ensure the intake of energy. In the lives of most trees, dormancy and withering may be the norm, as they accumulate strength and await the next burst of growth. The artwork employs the evanescent natural ambiance oscillating between visibility and invisibility to create a thought-provoking landscape ideorealm where the real and the unreal coexist.

Furthermore, the holographic circle and the square bonsai container construct a microcosm representing the concept of "Heaven is round, Earth is square" [9]. Within this miniature world, a twining tree extends endlessly, growing freely. Chinese bonsai is an ancient art form that embodies the aesthetic taste and wisdom of ancient Chinese literati. This artwork brings the aesthetic ambiance of holographic technology closer to the artistic ideological content of ancient China. This wisdom and ideology guide human in discovering the beauty of nature, learning to cooperate with nature, integrating with tradition, and utilizing modern technology to create an ideal home where humans and nature harmoniously coexist.

2.2 Pine Manifestation

Artwork "Pine Manifestation" (Figure 4) focuses on the evergreen pine tree, aiming to convey the essence of eternal life. In China, the pine tree is considered a symbol of longevity. The presence of pine trees can be seen in classical imperial gardens as well as modern residential areas. Pine trees have also been a popular subject in Chinese landscape paintings, carrying rich cultural symbolism and humanistic sentiments. In Xu Beihong's masterpiece "Twin Pines" (Figure 6), two pine trees are depicted, symbolizing companionship and displaying robust trunk structures and lush interlacing branches, vividly expressing their vigorous vitality. Using indigo dye as the base and dense ink dots and strokes, the pine needles are portrayed, capturing the abundant foliage and intricate branch formations. The outline of the trunk is depicted with square brushstrokes and dark ink, creating dynamic and winding lines that embody the grandeur and vicissitudes of the pine wood. In addition to Chinese artists, many foreign artists have also expressed their appreciation for pine trees. For instance, the French photographer Marc Riboud captured the ethereal play of light and shadow on the contours of pine trees, juxtaposed with mist, creating a romantic and majestic natural scenery (Figure 6).

Figure 4. Pine Manifestation, 2023.

Figure 5. Twin Pines,' painted by Xu Beihong in 1928 (53cm × 48.7cm), currently housed in the Palace Museum (Forbidden City).

Figure 6. Huangshan Sacred Mountains, Marc Riboud

The artwork "Pine Manifestation" integrates the holographic "triangle" with a circular bonsai container, creating a balanced miniature world within the space. In the artwork, the hologram breaks the silence of the bonsai environment under the illumination of light, and the highlighted triangles bring a unique visual expression. On one hand, the triangle's inherent mechanical advantage strengthens the common impression of the pyramid-shaped crown of a pine tree, while also creating a stable viewing experience. On the other hand, the aesthetic appeal innate to triangles emphasizes the hierarchical spreading structure of the pine tree, and the triangular hologram seems to establish a sense of order, infusing the artwork with vitality. In the coexistence space of the pot, tree, and holographic triangle, it creates a beauty of order, rationality, and abstraction.

Considering that one of the most distinctive features of pine trees is their needle-like leaves, typically arranged in clusters of 2, 3, or 5 needles, which cover the entire branches, they possess distinguishing characteristics and aesthetic value. Therefore, "Pine Manifestation" also expands upon a second viewing experience. With the assistance of light, the green holographic image and the silver pine needles appear and disappear, with light, shadow, form, and colour harmoniously echoing each other. It resembles a delicate painting created within the frame of a camera's window, as if capturing a unique scene from the vast world, allowing us to appreciate the joy of ancient literati in creating landscapes and explore the mysteries of nature. Thanks to the presence of light, the hologram and various natural elements achieve harmony and integration, while the involvement of the hologram enhances the interplay between reality and illusion, density and sparsity of the pine needles. This gives movement to the various elements in the composition in a rhythmic manner (Figure 7), portraying a poetic landscape imagery. It evokes a subtle sense of the ancient Chinese philosophical concept of "one produce two, two produce three, and three produce all things."[10]

Figure 7. Dynamic images of holograms and pine needles under light.

2.3 Manifestation of Seed

The artwork "Seed Manifestation" aims to rethink the process of fruit tree fruition. In a narrow sense, the fruition of fruit trees is a pattern of plant reproduction, where fruit trees pass on their DNA through this process. In a broader sense, the fruition process involves the transfer of energy, intergenerational inheritance, and the passage of time and space, encompassing a series of micro and macro changes that are an inherent and objective law of succession.

At first glance, the fruit tree in Figure 8 is constructed from artificial wooden strips for its trunk and branches, giving it a distinct angular and mechanical appearance. The green holographic leaves are attached on the wooden strips, adding a sense of technology and mystery to the entire artwork. It constitutes a modern installation artwork that subverts the audience's inherent perception of fruit trees relying on elements such as sunlight and soil for growth. However, beneath the surface of these modern elements, traces of history can be found. The branches of the fruit tree have been stained black with ink, presenting a gradient effect of varying depths under the light. Underneath the fruit tree, there are ink marks created by ink flowing and dripping, resulting in a variety of ink patterns that create a sense of casual freedom.

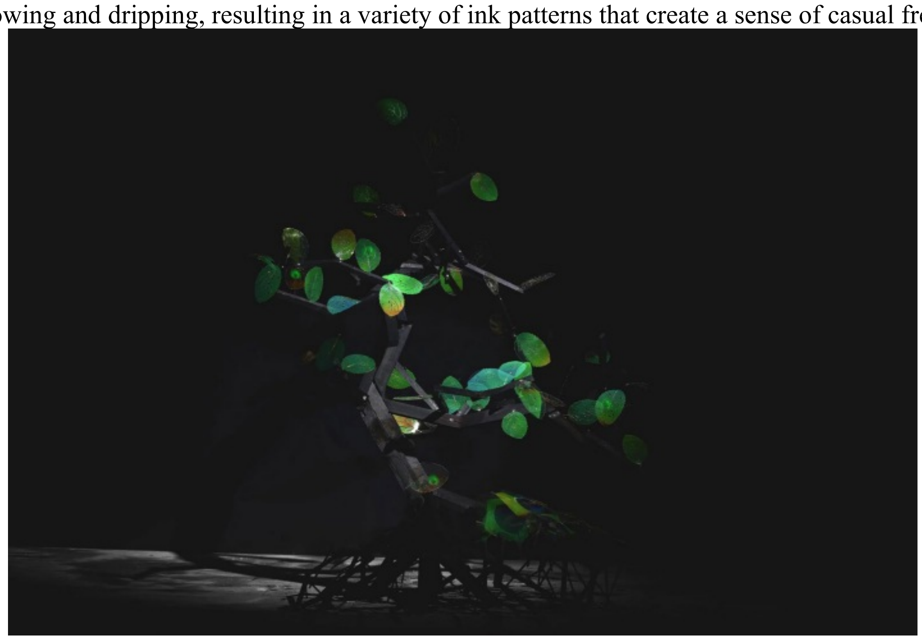

Figure 8. Seed Manifestation, 2023.

When the viewer's gaze focuses on the holographic leaves, the hidden fruits (apples) inside become faintly visible (Figure 9), giving the audience an inexplicable sense of harvest and arousing their desire to explore and obtain. It is reminiscent of Adam and Eve facing the temptation of the apple (Figure 10). The ink stains on the ground seem to be traces left by those who desired the fruits, immersing themselves in the joy of gaining, disregarding their own image and the risk of being stained by ink. They eagerly seize the fruits, even if some leaves have already been damaged by insects. Meanwhile, the fruit tree stands quietly like a selfless giver, silently offering the fruits of its hard work. However, these fruit pickers may not realize that it is through them that the fruit tree spreads its seeds to distant places, ensuring its own succession. The tree itself is just a part of the ecosystem, subject to the operating principles of the entire system. The fruit tree and humans seem to have formed a stable relationship in this mutually interactive and mutually beneficial environment, achieving mutual gains.

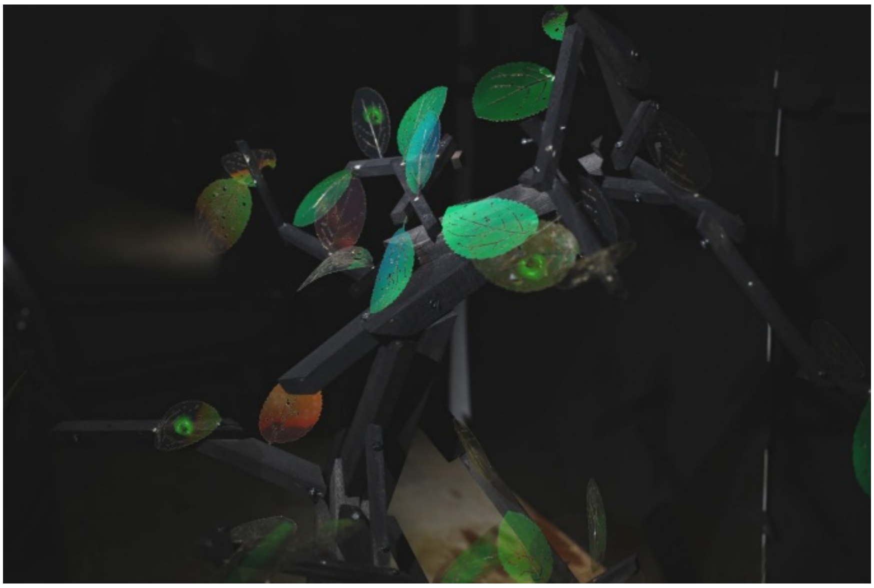

Figure 9. Detailed close-up view with the hidden apple in the artwork “Seed Manifestation”.

Figure 10. Adam and Eve,' Albrecht Dürer, 1507.

"Seed Manifestation" expresses the ecological cycle and logic of similarity between natural creations and man-made objects. From natural wood to artificial wood, from natural leaves to artificial leaves, from natural fruits nurtured by sunlight, air, and water to human-made engineered human fruits, it explores various aspects of civilization and culture, desire and hope, dedication and competition, game and cooperation, as well as exploration of regeneration and rebirth.

3. SUMMARY

The "Manifestation" series incorporates ancient Chinese creative thinking and employs the expression of bonsai. By "immersing in objects," the authors places natural and artificial elements in the same space, merging natural laws with human factors and expanding our understanding of the universe, prompting contemplation of life. The artworks, illuminated by light, create new ideorealm and seek balance between the visible and the invisible, exploring the symbiotic relationship and inherent ecological logic between nature and humanity. Furthermore, through the practice of the "Manifestation" series, the authors discovered the high adaptability, amusement, and integration of holographic images based on photopolymerization, allowing for artistic expression and presentation on various themes.

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An Exploration of the Concept of Touch through Holographic Artworks

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ABSTRACT

"Touch" serves as a means through which individuals perceive, understand, and explore the world. Holography, as an innovative artistic medium, allows the presentation of three-dimensional objects under light, providing a tactile sensation and offering strong interactivity and engagement. This paper introduces three sets of holographic artworks created between 2019 and 2022, with "touch" as the exploratory focus. The first animated artwork, "Mushroomhood", explores how humans, embodied as mushrooms, interact with society. The second installation artwork, "Rules and Rulers", explores the ways and principles of "touch" (the principle of touching things). The third installation artwork, "Within Reach", explores the subtle touch and dialogue between gestures and sign language.

Keywords: Holographic artworks, touch, artistic medium, Installation, animation

1. INTRODUCTION

1.1 "Touch"

In Chinese bronze inscriptions (a type of Chinese ancient characters that cast or engraved on bronze wares), the character "触" (touch) consists of three components: "牛" (ox), "角" (horn), and "长" (long) (Figure 1). It directly represents the meaning of the character "触" and belongs to a compound ideogram. It originally served as a pictographic character represents pushing against or collide by horn [1]. Later on, the character "触" extended its meaning to include concepts such as resistance, collision, and offense. For example, when two horns collide, it implies a struggle where both parties inevitably come into contact. Thus, "触" also implies touching or coming into contact, and through collision, it further extends to the concept of offense. Examples include phrases like "触怒龙颜" (offending the dragon's dignity) and "触犯天条" (violating heavenly laws). Additionally, in an abstract sense, "触" can refer to emotional changes caused by certain stimuli, as in "感触" (emotional response) and "触动" (being touched).

Figure 1. Ancient Chinese bronze inscription for character "触" (1300BC- 219BC).

Throughout different periods of human history, the concept of "touch" has been widely present in great works of art. It can be said that the cultural significance of "touch" has fostered human development. For instance, one of the most renowned works of art from the Italian Renaissance period is Michelangelo's fresco painting "The Creation of Adam" in the Sistine Chapel (Figure 2). The painting depicts God reaching out his hand to touch Adam's finger, bestowing upon him the gift of life. This scene is highly complex and rich in symbolic meaning, captivating audiences even today and inspiring people to explore the profound meanings behind this artwork [2].

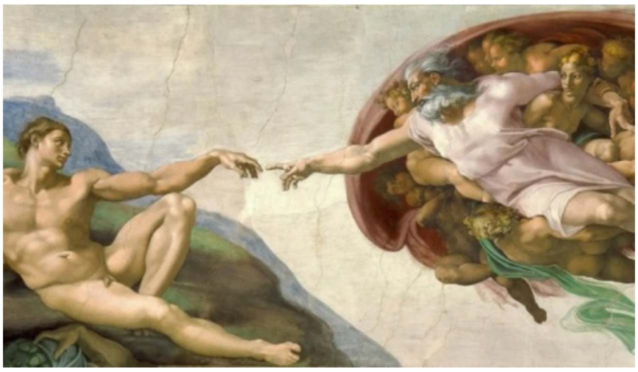

Figure 2. Michelangelo, The Creation of Adam, from the Sistine Chapel Ceiling, 1508-1512, image courtesy of The Sistine Chapel, Rome.

In 2021, the Fitzwilliam Museum in Cambridge, UK, curated an exhibition titled "The Power of Touch," which explored the fundamental role of touch in human experience by bringing together various artworks spanning 4,000 years of human history. The exhibition featured a wide of multi-media works, including ancient Egyptian limestone sculpture, illuminated manuscripts, prints (Figure 3), as well as objects of religious and spiritual significance, love tokens, and faith rings from around the world [3]. The topic of "touch" has been a subject of continuous interest from ancient times to the present.

Figure 3. Handprint of Emil Orlik (1870-1932), Katrin Bellinger Collection, example exhibit from the exhibition "The Power of Touch" at the Fitzwilliam Museum, Cambridge, UK.

1.2 Hologram

Hologram, as a medium, provides a unique way to record and reproduce three-dimensional space on a flat surface. The resulting super-realistic, naked-eye 3D visual effects can deceive the viewer's eyes [4]. Consequently, when experiencing holographic imaging, viewers often feel an impulse to touch the objects within the image space. Moreover, if the viewer's head starts to move, holographic imaging can seamlessly and naturally transition from static to dynamic presentation, further enhancing its interactivity.

Margaret Benyon is one of the earliest artists to utilize holographic technology as a medium. Based on the research of environmental psychologist D. Canter, she observed that most people react to holographic images with "surprise, fascination, or even shock," and some viewers are unable to distinguish between holographic images and real objects [5]. Furthermore, she discovered that viewers can experience an "unspoken illusion" even without any professional background, indicating a form of contact between holographic imaging and the mind.

1.3 Overview of Three Artworks Exploring "Touch"

The three sets of artworks, focusing on the theme of "touch," were completed between 2019 and 2022. "Mushroomhood" (Figure 4), "Rules and Rulers" (Figure 5), and "Within Reach" (Figure 6) respectively explore the ways of touch, the principles of touch, and the self-dialogue of touch.

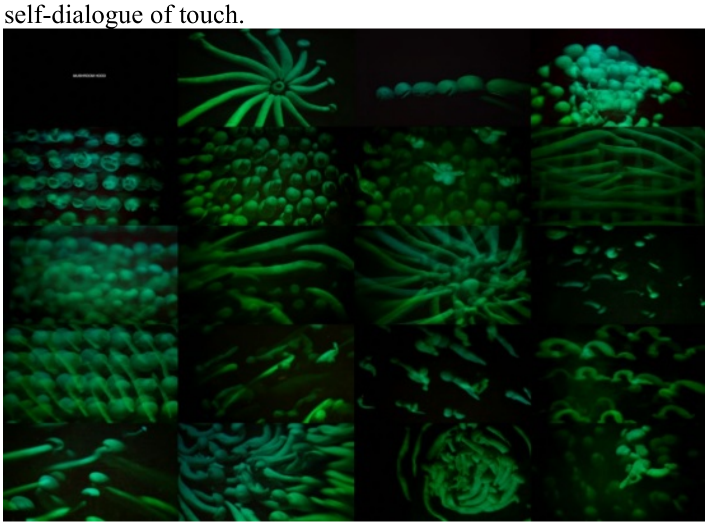

Figure 4.Mushroomhood, 2019, storyboard from the holographic animation, duration: 2:42'.

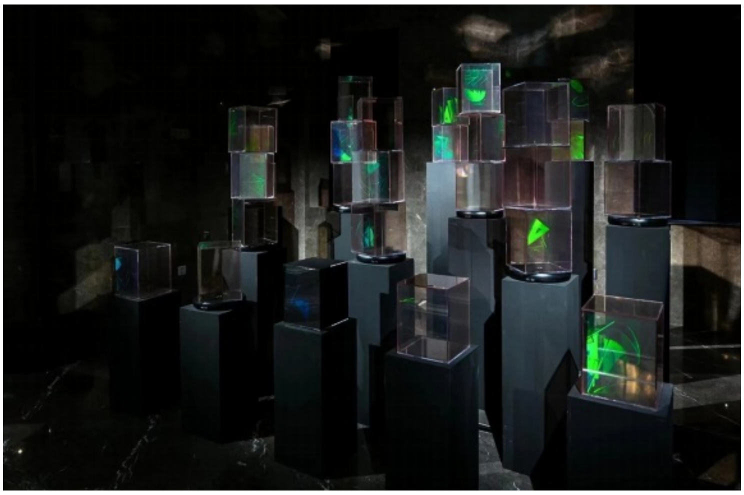

Figure 5: Rules and Rulers, 2022.

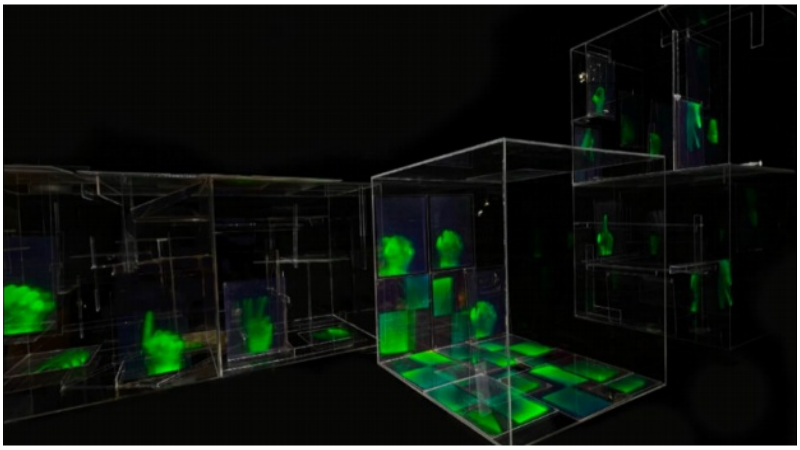

Figure 6: Within Reach, 2022.

“Mushroomhood” explores and reflects on the concept of how to establish contact. The inspiration for the artwork came from a chance encounter with clusters of mushrooms placed in a box at a food market (Figure 7). This discovery sparked contemplation as the forms, postures, and expressions of the mushrooms in the box bore a striking resemblance to human beings, appearing as if they were human incarnations. Subsequently, extensive research was conducted on mushrooms, including studies of ancient rock carvings featuring mushrooms [6], Figure 8 shows one of the rock carving examples. Mushrooms depicted in Renaissance paintings (Figure 9) [7], mushrooms in Enlightenment-era scientific illustrations (Figure 10) [8], and contemporary artworks with mushrooms as the subject (Figure 11) [9], among others.

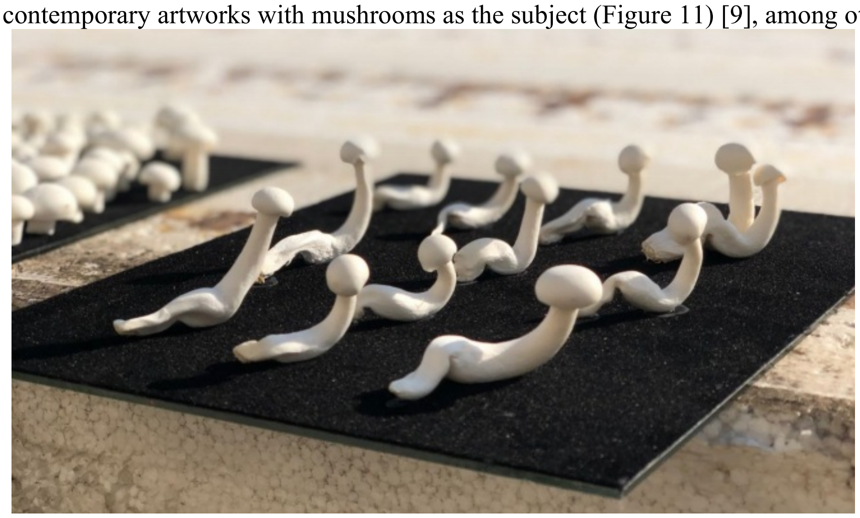

Figure 7. Selected mushrooms during the art creation process.

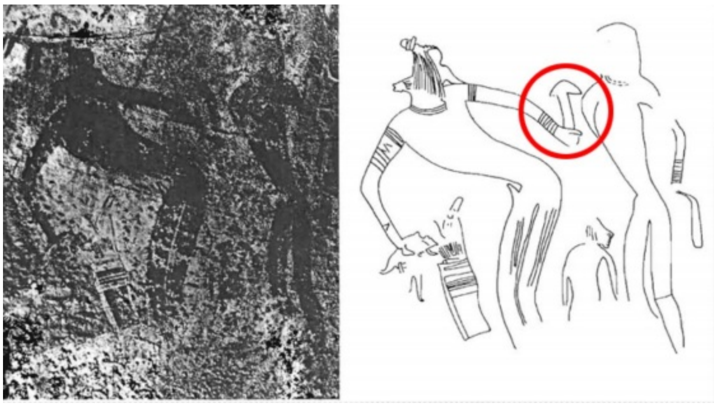

Figure 8. Left- rock relief painting, reconstructed sketch of the image on the left, Sit Zarift site, Tasiri, Algeria, 7000-5000 BC.

Figure 9. The Agony in the Garden (2nd), Andrea Mantegna, 1456-1459.

Figure 10. Forest Floor with Mushrooms, Snakes, Toad and Lizard, Otto Marseus van Schrieck, 1662.

Figure 11. Mushroom Death Suit, Jae Rhim Lee.

As the research progressed and contemplation of the real experiences deepened, the artist discovered that establishing contact with others or objects in the present requires a special skill. Additionally, through careful observation and selection of extensively cultivated mushrooms, it was found that the mushroom's growth environment and way of existence mysteriously reflect the state of human beings in society. Ultimately, over 200 holographic images depicting "humanized mushrooms" were created using a radiative approach on an optical platform, and the artwork was presented in the form of an animation.

"Rules and Rulers" reflects on the principles of touch. Dale Carnegie, a renowned American writer and psychologist, argued that in human interactions, one must find the right balance [10]. This may involve factors such as intensity, angle, temperature, and more. The artwork "Rules and Rulers" constructs a dynamic spatial order incorporating triangles, circles, and squares, using a triangular board, ruler, and protractor marked with precise scales.

"Within Reach" aims to explore things that one desires to touch, providing subtle indications of interpersonal contact from different perspectives. Light, space, and movement are central to this artwork. In human life, some things are within reach, with everything within grasp, while others are beyond reach, with everything slipping out of control.

2. ARTWORK "MUSHROOMHOOD"

Mushroomhood is ultimately presented as an animation composed of 200 digital holographic images (Figure 12). It meticulously portrays mushrooms that embody various techniques, including:

- Cross arts: Mushrooms with irregular plate-like shapes, intertwined, clustered, crowded, and overlapping (Figure 13).
- Etiquette arts: Mushrooms exhibiting certain constraints in appearance, behavior, demeanor, ceremony, speech, and conduct, constituting a set of behavior norms recognized by all (Figure 14).
- Curl arts: Mushrooms curling their bodies when sensing proximity to "danger," attempting to adopt a defensive posture for self-protection (Figure 15).
- Expand arts: Expressing the importance of having an open mind and being flexible in interpersonal interactions (Figure 16).

- Solitude arts: Learning to embrace solitude and refusing to conform to societal norms (Figure 17).
- Wither arts: Dealing with the attitude towards aging and death (Figure 18), and more.

These various techniques are used to depict the mushrooms in a multi-faceted manner, creating a rich and nuanced exploration of the concept of touch in the artwork "Mushroomhood."

Figure 12. The holograms that make up the animation “Mushroomhood”.

Figure 13. Cross arts.

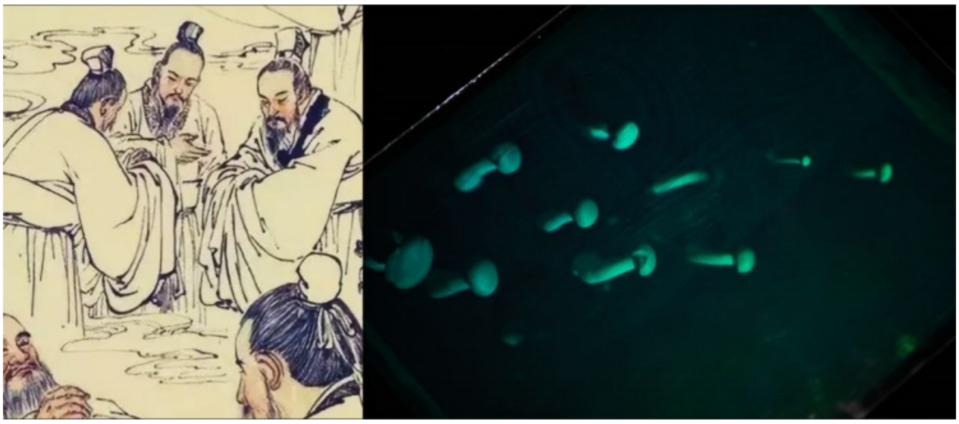

Figure 14. The left image depicts a common posture in ancient Chinese etiquette, while the right image shows mushrooms in the artwork " etiquette arts" exhibiting a similar posture to the one on the left.

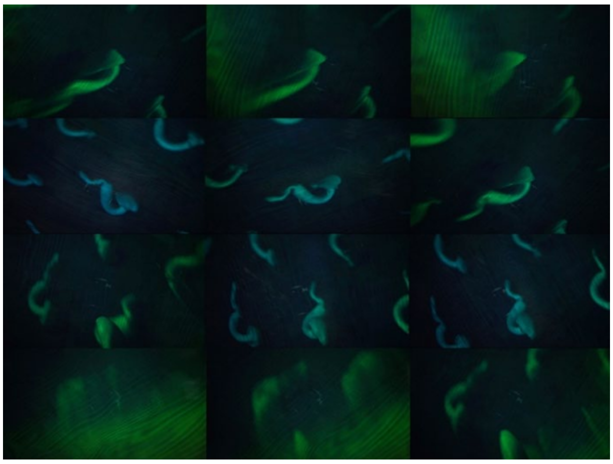

Figure 15. Curl arts

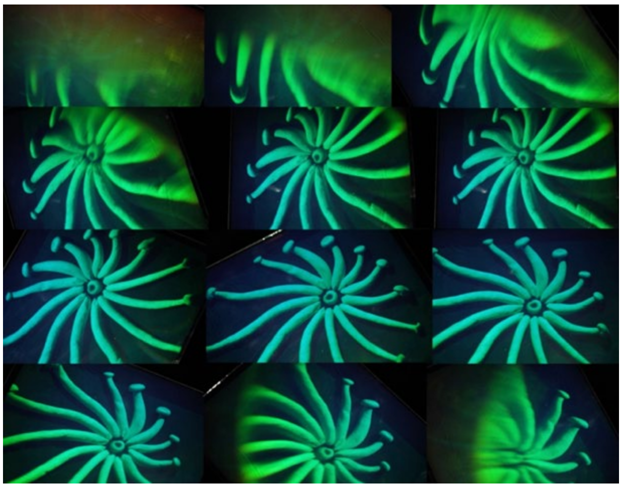

Figure 16. Expand arts.

Figure 17. Solitude arts

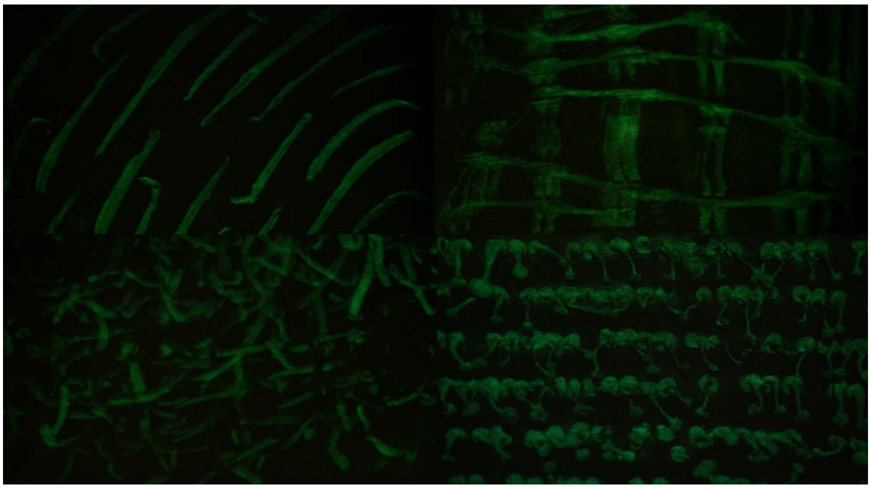

Figure 18. Wither arts

In the animation "Mushroomhood," mushrooms, these magical creatures, have unconsciously transcended their individual existence and become familiar faces to humans, blending into their daily lives. Just like the mushrooms in the game "Super Mario" that grant Mario the extraordinary power of regeneration, helping him overcome various levels and accomplish his goals. The magic mushrooms also enable human redefine reality, surpass it, and create it.

This animation depicts the state of mushrooms in a green fantasy land. Green, as a color with dual associations, can not only represent the dreamland in life but also reproduce the fantasy in memories. In this work, mushrooms are portrayed as active beings during midnight (Figure 19). They try to bring clarity to the ephemeral nature of life. When moonlight illuminates and the bell rings, the mushrooms showcase past memories and personal experiences. Fleeting smoke, rhythmic beats, and the passage of time revive the green of youth, allowing the energy of life to radiate. Joy and sorrow, encountering and parting, self-appreciation in solitude, curling up gracefully (Figure 20), crossing in complexly (Figure 21), and lingering ineffably (Figure 22), all these states belong to “Mushroomhood”. The relationships among mushrooms resemble a tango, filled with tentative attacks and solid defenses, individual’s solitude crowds’ gathering. Mushrooms is a species with a split personality. They are noble, vulgar, kind and thoughtful at the same time. Human nature coexists with mushroom nature, share the same fantasy with the universe, and build the community of life together.

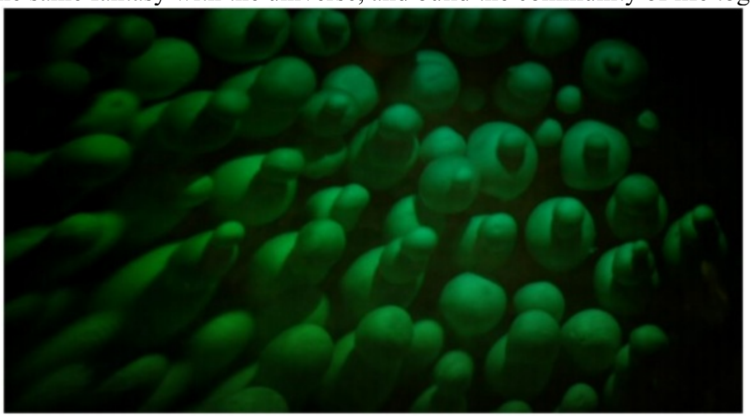

Figure 19. Scene in the “Mushroomhood”, appears in the animation at 01:04.

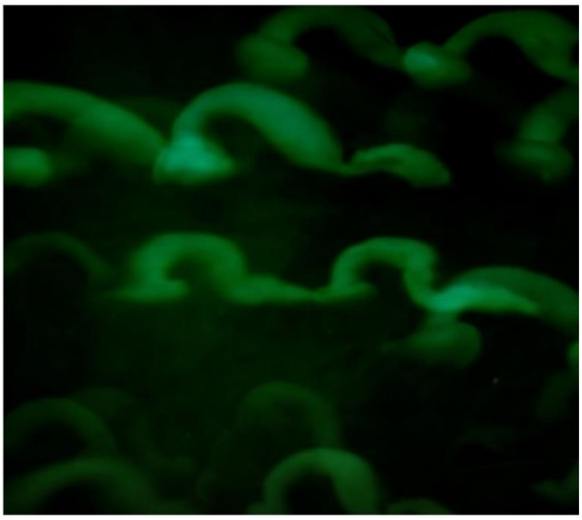

Figure 20. Scene in the “Mushroomhood”, appears in the animation at 01:56.

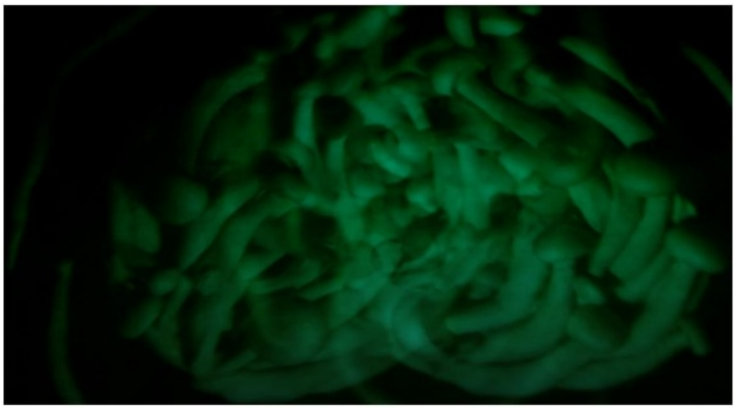

Figure 21. Scene in the “Mushroomhood”, appears in the animation at 02:07.

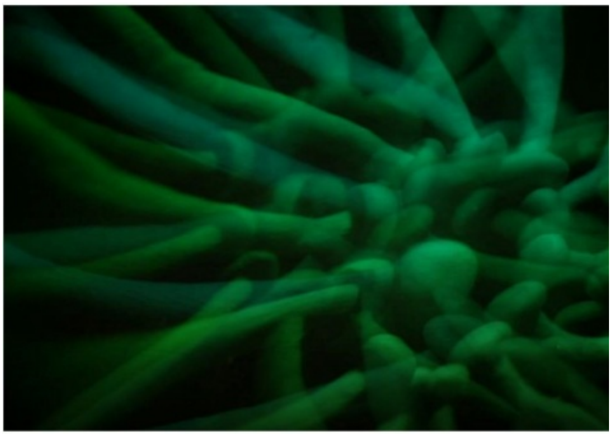

Figure 22. Scene in the “Mushroomhood”, appears in the animation at 01:40.

This artwork is based on Hypsizygus marmoreus, one of the most common mushrooms in the market. Over ten thousand mushrooms were explored and the human-like forms were selected for further digital creation. By analysing the movements and forms of mushrooms, the artwork was created through a combination of digital holographic printing and traditional analogue holograms. As shown in Figure 23, more than 10 different percussion instruments from various regions were mixed in, including marimba, thunder drum, angklung, qing, etc. to convey the audio-visual effect of symbiosis and resonance between humans and mushrooms.

Figure 23. Partial percussion instruments used in the artwork "Mushroomhood".

3. ARTWORK “RULES AND RULERS”

The artwork "Rules and Rulers" attempts to explore the complex dimensions of human interaction and the corresponding scales involved. The Greek philosopher Protagoras said, “Man is the measure of all things” [11]. Everything in the world has its own scale, and the same applies to human interactions. When dealing with parents, romantic partners, colleagues, friends, and strangers, it is necessary to understand human nature while maintaining appropriate boundaries.

During the Warring States period in ancient China (475 BC-221 BC), the famous philosopher, thinker, and educator Meng Ke (Mencius) stated, “Nothing can be accomplished without rules [12].” Even today, this statement continues to have a profound influence on people. It reveals an important truth that in everything we do Society is formed by the aggregation of individuals, and social activities are the activities of individuals. Individuals have different motivations and goals for their actions. Therefore, if there are no rules to regulate behaviour, people will act as they please, and society will descend into chaos. For example, in the past few years during the COVID-19 pandemic, if society had not established certain rules, it could have fallen into disorderly chaos. Moreover, from interactions between nations to daily interactions between neighbours, there must be certain constraints; otherwise, conflicts and even wars are inevitable., we need to have a sense of scale, understand boundaries, and abide by them.

Since birth, each person is more or less constrained by one or several invisible “rulers” that shape their growth trajectory. In this process, these rulers play an important role in measurement and evaluation. In the holographic installation artwork "Rules and Rulers," the artist constructs a multidimensional space using the most common measuring tools such as rulers, compasses, and protractors (Figure 24). These tools are affixed to the six faces of individual boxes of equal volume (front, back, left, right, top, bottom) (Figure 25). When each face of the boxes is covered with holograms and placed in space (Figure 26), it appears as if a Stonehenge-like structure is created, filled with eternal, unknown, and yet worth exploring order (Figure 27). Additionally, the presence of the rotating disc at the bottom seems to disrupt the balance between tradition and modernity in the order of scales, but it preserves the conservation of energy.

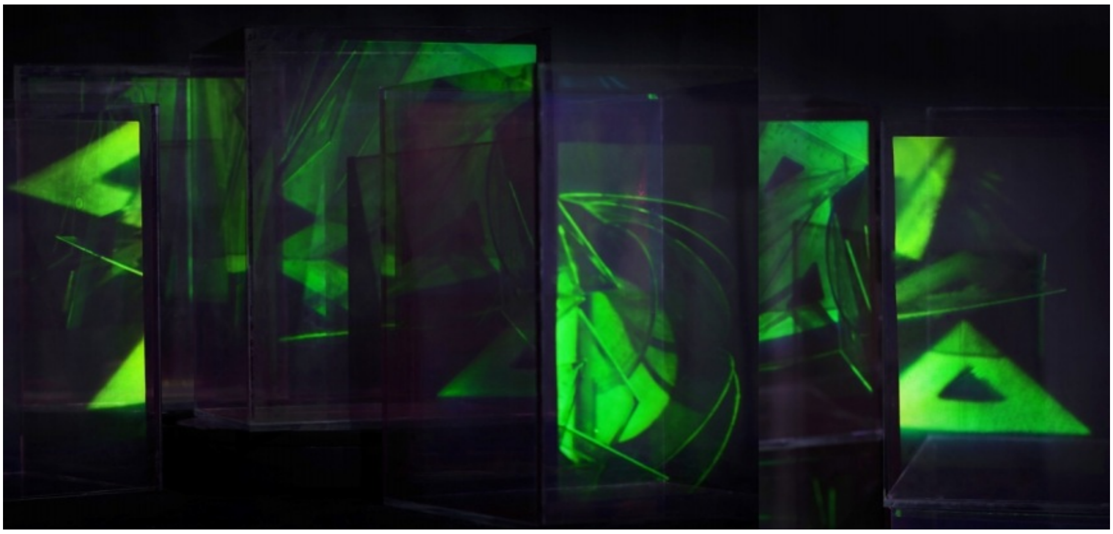
Figure 24. The holographic images constructed using rulers, compasses, and protractors.

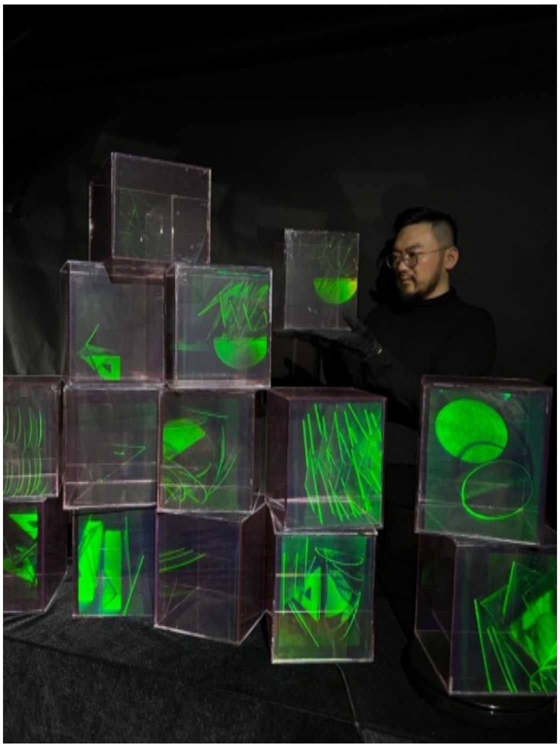
Figure 25. Artist Shuo Wang interacting with the six faces.

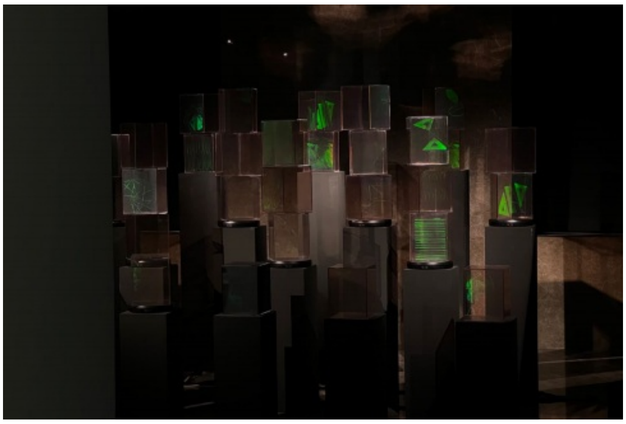

Figure 26. The installation “Rules and Rulers” exhibited at the 2022 Hong Kong-Macau Visual Arts Biennial Exhibition, showcased at Beijing Fang Exhibition Hall, Beijing.

Figure 27. Stonehenge in Bath, United Kingdom.

In an era of continuous digitization and informatization, whether it is virtual interaction in the metaverse or communication in the real world, humans will face more opportunities and greater challenges. Humans will constantly explore spatial perspectives and control movement speed in order to better balance the intensity, temperature, transparency, and other aspects within themselves.

4. ARTWORK “WITHIN REACH”

The holographic installation "Within Reach" explores the connection between hands, touch, gestures, and implications. In the artwork, green hands are placed under and within the light, radiating and shining through the light. They exist and interact with each other (Figure 28). The artwork uses the artist's hands as the medium to explore the ecological balance within the human self. It forms a dialogue between the left and right hands, going beyond the gestures themselves to explore one's operational abilities and potential for manipulation. It combines elements of acquisition and sacrifice, gain and loss, the void and reality, digital and computational aspects, and emotions. All the senses, existence, and void blend in this transparent interwoven multidimensional space.

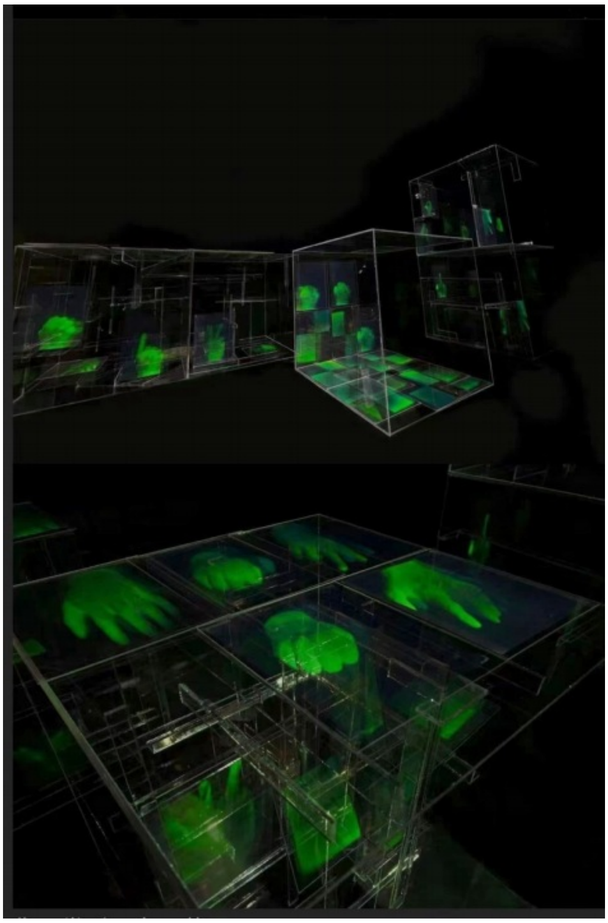

Figure 28. The holographic installation artwork "Within Reach" from different perspectives.

"Within Reach" incorporates the unique Chinese way of expressing numbers, where one hand can represent numbers 1 to 10 (Figure 29). These subtle hand gestures can be used for daily communication, and the graphic representations formed by these numbers have different interpretations in various contexts. For example, the gesture "2" represents not only the number 2 but also success (Victory). The gesture "5" represents not only the number 5 but also goodbye, celebrating with a high-five, and other symbols. Additionally, the artwork incorporates many holographic blocks resembling pixels. These blocks are arranged in a regular pattern, seemingly following a particular order, and display unique characteristics such as a sense of order, ambiguity, and a contemporary vibe when exposed to light.

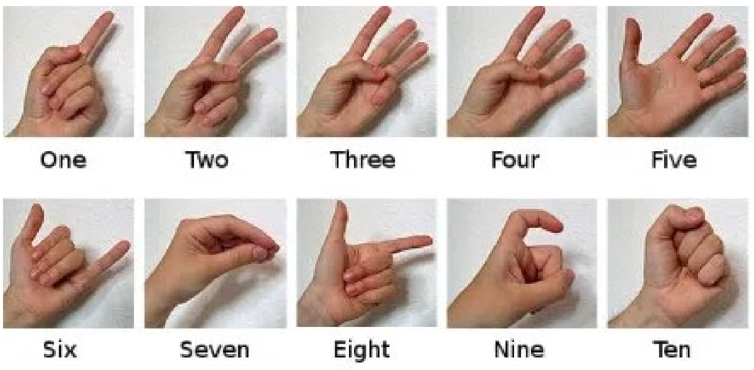

Figure 29. Chinese hand gestures representing numbers 1 to 10.

Acrylic is a specially processed plastic material with stable performance and lightweight quality, making it uniquely advantageous in the application of installation art. The artwork "Within Reach" extensively uses Polymeric Methyl Methacrylate, commonly known as acrylic panels, in its design. From the perspective of spatial art, this installation artwork has specific requirements for its presentation. After multiple tests, the team ultimately chose to use 5mm thick panels for the creation of the artwork. The artwork needed to address the holograms multidirectional presentation within a physical structure. The number of holographic display layers and their positioning required continuous experimentation and optimization during the production process. Thus, "Within Reach" grows like extending "tentacles" from a single box to a combination of multiple boxes for presentation. Additionally, due to acrylic's ability to be cut and adhered into various spatial shapes, the spatial structure can be constructed, disassembled, and recombined at will, making the presentation of holographic images malleable and flexible, greatly unleashing artistic creativity. The freedom eliminates the boundaries of holographic images, creating an alternating narrative between images. The compactness of holograms within acrylic boxes creates a rhythmic viewing experience for the holographic art installation. Moreover, the ethereal quality it presents opens up the viewer's imagination.

The acrylic grid space provides an infinitely expandable spatial structure for holograms. Each hologram is arranged one after another, with a specific-sized base placed in the transparent space to ensure that the viewing height of the holographic image remains parallel to the viewer's line of sight. This spatial display environment ensures that viewers can have a more holistic viewing experience of the artwork, better promoting interactivity, participation, and the continuous movement of light during the viewing process.

In addition, the artwork contains multiple spatial attributes. When facing the installation, the viewer's gaze usually transitions from the overall space to the local space and then to the space constructed by holography. This continuous spatial switching experience seems to help expand the viewer's understanding of the real and virtual worlds. At the exhibition site of the 2022 Asian Digital Art Exhibition (Fig30), the deep purple background adds a certain sense of mystery to the artwork.

Figure 30. “Within Reach” exhibited at the 2022 Asian Digital Art Exhibition.

As the viewer moves from one side of the artwork to the other, in each holographic image, hands in different gestures change along the X, Y, and Z axes at different speeds, revealing the interactivity of the holographic space in a dynamic way. Furthermore, the artwork uses motion speed as a clue to connect the viewer with the images. Viewers can freely control the rotational speed of objects in the holographic images according to their preferred speed, allowing them to appreciate the holographic artwork in their own preferred way of movement. This means that each viewer's body and mind can experience a unique virtual and real journey through time and space.

Holographic installations can help viewers better understand holograms, enhance the visual impact of holograms, and stimulate dialogue among viewers in specific environments. It transforms the conventional wall-mounted display into a spatially free display, enriching the media characteristics of holograms. Through the integration of light, space, and movement, it provides viewers with a better spatial and temporal interactivity and participation. At the same time, the artwork innovatively combines and integrates mixed media, satisfying the current need for diverse artistic development.

5. SUMMARY

This paper explores the concept of touch through three holographic art pieces, delving deep into the ways, principles, and dialogues of touch. Touch is an eternal topic worth discussing, as it constantly navigates between the realms of matter and spirit, macro and micro, virtual and real, and quality and conservation. Touch is an important means of perceiving the world, and holographic art enhances our sensitivity to touch. The years 2019-2022 were a unique period in human history, and holographic art practices helped us better engage with the world and understand our surroundings. Thegreen holographic images represent a positive future ecosystem and cycle.

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Revisiting history through virtual reality holographic art

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ABSTRACT

This paper presents two artistic projects that use VR sculptural drawing holography to revisit and revive places and people from the past.
The first project, titled 'Marna', is an installation comprising a VR hologram of a historical building in Bucharest, Romania which was recently demolished, and a large-scale ink drawing and print of the new building that was erected in its place.
The second project follows up on my recent ink illustrations for 'Project Han', a collaboration with Studio K, bringing together historical figures of South Korea and related architecture.
The two projects presented here employ the medium of VR holography to draw attention to stories of people or places that no longer exist, at the same time as expressing their frailty. A space of meditation on history is thus established and new dialogues open between artwork and viewer.

Keywords: VR holography, holography art, sculptural drawing, surface relief digital holography.

1. INTRODUCTION

Due to its ability to record light fields with remarkable accuracy, holography has often been used as a method for producing copies of historic, museum artefacts. The Hellenic Institute of Holography, whose principal goal is 'the use of display holography in the preservation, recording and public visual dissemination of artifact items from this cultural heritage' [1], have carried out numerous projects that aimed to record cultural artefacts through their original holographic technique known as "Optoclone" [2]. The Centre for Modern Optics in North Wales also collaborated with several major museums to create analogue holograms of various artefacts which were then displayed in a travelling exhibition [3]. In addition, colour holograms of paintings have been created by Yves Gentet in collaboration with the Louvre, and by Hans Bjelkhagen and Dalibor Vukicevic. As far back as the early 90's, Australian Holographics produced large scale rainbow holograms of items from the Museum of South Australia [4].

Many artists who have successfully distanced themselves from a simplistic use of holography shy away from an obvious display of the mimetic function of analogue holograms, in their quest to find the true nature of holography. Nevertheless, holographic art too has sometimes been used as a 'window to the past'. Admittedly these works acquire more of an historic character with the passage of time. Paula Dawson's *There's No Place Like Home* (1999) uses a large hologram as a window through which one can see the interior of an ordinary flat [5]. The real space and configuration of objects that the hologram captures in glorious detail is far removed both in space and in time, whilst what we are confronted with is an uncannily accurate copy of that reality. Patrick Boyd's holographic stereograms such as 'Jackson Makes it to Manhattan' (1990) and 'Atlantic City' (1990) document everyday scenes encountered during his walks. Recorded with a handheld 35mm camera, these artworks have a raw appearance which, added to the gritty subject-matter contributes to the documentary quality of the project and its 'window-to-the-past' function [6]. David Pizzanelli appropriates Edweard Muybridge's photographic sequences of bodies in motion to create multiplex holograms. Although his primary aim is to explore the (hitherto ignored) parallax information contained in Muybridge's photographic material, an interesting side effect is the recreation of the three-dimensionality and motion of the original subject [7]. In 'Passing Time, a Distant Memory', Pearl John combined several chronologically ordered family photographs into a single hologram. As the viewer moves in front of the artwork the rearmost image appears to move closer to the hologram plane/present time and thus, according to the artist, the depth of holographic space is used to represent the temporal dimension [8].

The artworks presented in this paper are digital holograms. By contrast with the examples mentioned above, they do not capture or reproduce an existing item or scene – their content is created by hand and is therefore twice removed from their reference. A consequence of this method is that the time spent creating these sculptural drawings highlights the meditative quality of the creative process – painstakingly constructing an artwork by means of traditional methods allowed me the mental space necessary to engage with the subject, to meditate on its meaning, on the dialogues that can be opened by bringing these stories into the public space in the form of holograms.

2. THE HISTORIES BEHIND THE ARTWORKS

The real subjects of my artworks, namely Empress Min, Yu Gwan Sun, and the building Marna, all have in common a premature (even violent) ending. Empress Min and Yu Gwan Sun's assassinations were meant to put an end to the ideals they represented, but instead turned them into symbols of rebellion and the fight against oppression. The Marna movie theatre was allowed to decay for years, set on fire, and finally demolished, as part of a great plan of urban modernisation. Instead, along with the other demolitions done in the same neighbourhood, it became one of Bucharest's unhealing wounds, a prime example of bad, abusive local management, and a sad story that many people still deplore.

2.1 Empress Myeongseong and Yu Gwan Sun

'A possible portrait of Empress Min' (2023) and 'A girl from Ewha Women's School' (2023) both follow up on two of the illustrations I have created in 2022 and 2023 for Project Han, a collection of ink drawings depicting some of South Korea's most prominent historical figures, together with related historical buildings and artefacts.

Figure 1. 'Project Han' (2022-2023) by Ioana Pioaru, A6 ink drawings on paper (left), Empress Myeongseong, from Project Han (centre), Yu Gwan Sun, from Project Han (right).

Empress Min, known as Myeongseong (1851 – 1895), was a significant figure in Korean history during the period leading up to Japanese occupation. A passionate advocate for her nation's progress, she championed the establishment of schools, newspapers, and hospitals, and extended a warm welcome to Christian missionaries. Assertively challenging Japanese influence, she emerged as a symbol of resistance. However, her defiant stance eventually led to her assassination by the Japanese. Despite her influential role, very few images of Empress Min exist due to her deliberate decision to maintain a low public profile and avoid having her photograph taken. The portrait I utilised as a reference for my creation (Figure 2) is ambiguously titled 'A lady's maid in the Korean emperor's court.' This image is speculated by many to be of Empress Myeongseong, providing a rare glimpse into the persona of this impactful figure.

Figure 2. “A lady’s maid in Korean emperor’s court” Public domain, via Wikimedia Commons

A Japanese illustration of Empress Min and King Gojong (Figure 3) shows her in a similar attire.

Figure 3. Engraving from Japanese illustrated magazine "Fuuzokugaboo", Public domain, via Wikimedia Commons

‘A girl from Ewha Women’s School’ is inspired by the story of Yu Gwan Sun (1902 – 1920), who became a symbol of Korea’s fight for independence after being imprisoned and tortured for taking part in a march protesting the Japanese occupation of Korea. While in prison, she was offered a lighter sentence on condition that she would help the Japanese military police identify her fellow protesters. She refused even after severe torture and subsequently died from her injuries. The photo I used to draw her (Figure 4) is one of the few photographic portraits of her that exist today, and it was taken during her imprisonment.

Figure 4. Imprisonment card of Yu Gwan Sun, Public domain, via Wikimedia Commons

While I was reading about Yu Gwan Sun, I came across an article showing her alongside her colleagues at the Ewha Women's School, and an image of a room in the Seodaemun Prison Museum (Figure 5), the walls of which have been covered with imprisonment cards just like the one I used as a reference. Many of these cards show pictures of young women, whose stories are unknown but likely similar to Yu Gwan Sun's [9]. Although my artwork is inspired by the specific story of Gwan Sun, the likeness of the portrait I made of her is somewhat loose as I wanted to represent her status as a symbol of a struggle and of ideals shared by many.

Figure 5. Photo of Yu Gwan Sun and her colleagues (left) and photo of a room in Seodaemun Prison (right) [9]

2.2 Marna (2022)

'Marna' is a holography and drawing installation that was inspired by an old building in Bucharest, built in 1880. It initially hosted a theatre, then a cinema, first known as Marna, then as 'Cinema Feroviarul'. Popular knowledge has it that, in 1990, the tenants set the building on fire to get the local authorities to move them into better accommodation.

Figure 6. The building as it looked at the beginning of the 1900s (left) and in the 70s (right) [10].

When I was living in Bucharest in the early 2000's, I only ever saw the building as a ruin, with no roof and no windows, just two adjoining walls with trees growing inside, among piles of rubbish - a ghost of what used to be a 19th century, French neo-classical style building with beautiful ornaments still visible on its façade around 2009. I kept hoping that somehow a miracle would happen, and it would be restored to its former shape and glory. Instead, the more predictable scenario materialised, and it was demolished (illegally) along with many other houses in the neighbourhood.

Figure 7. The building in 2010, shortly before it was demolished [11].

3. REVISITING THE PAST THROUGH VR HOLOGRAPHY

VR sculptural drawing holography is a novel art medium that combines the qualities of traditional drawing with those of holography. The sculptural drawings are made by hand in virtual reality with Google Tilt Brush and printed as surface relief digital holograms [12]. They are drawn in black-and-white to emulate the aesthetic of traditional ink drawing on paper, my favourite artistic medium, but also to symbolise the transient and spectral character of the past.

3.1 'A possible portrait of Empress Min' (2023) and 'A girl from Ewha Women's School' (2023)

My depictions of Empress Min and Yu Gwan Sun are made through the medium of VR sculptural drawing holography - each stroke making up the portraits are drawn individually, by hand, in three-dimensional virtual space.
I used Google Tilt Brust to help me create the content of the holograms. To start with, I imported my drawings from Project Han into virtual space to use them as a references for my sculptural drawings, in a similar way that one would draw from a model or 'from life', in real space. The difference here is that, while in real space drawing the 3D

information from the model is compressed into a flat 2D rendition of it, in virtual space the visual information from the 2D references gives an idea of how to create the sculptural drawing, so to a certain extent the work is speculative (in the sense that I can only guess what a person's profile would look like just from a frontal-view visual reference).

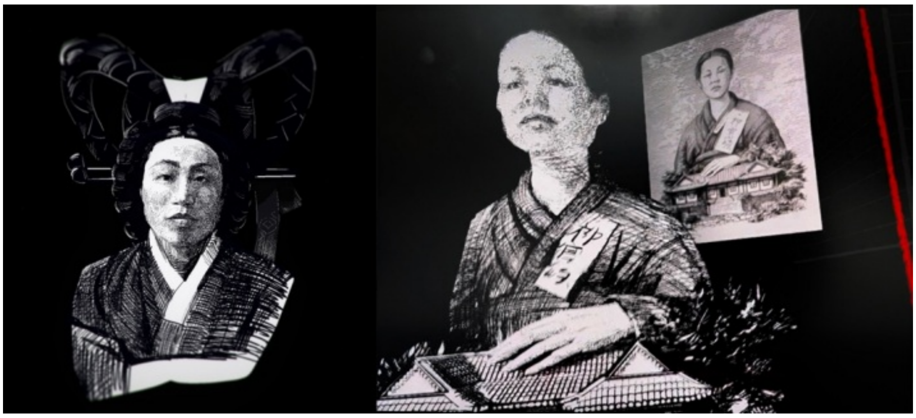

Figure 8. Captures from Tilt Brush: Empress Min, finished project (left) and Yu Gwan Sun, work in progress (right). In the image showing Yu Gwan Sun, the drawing used as a reference in virtual space is still visible in the background.

After deleting the reference images, I exported the project and then opened it with Blender. The next stages of the process are done in collaboration with Geola who are currently developing a tool for automating this postprocessing phase to enable artists to easily prepare the files for being printed. Briefly, the process consists of reapplying the correct colours to the volumes, setting up the 'holoplane' (a virtual plane that simulates the holographic plate) and positioning an animated camera at the correct distance from the holoplane using the parameters specified by the company making the holograms.

For this project, I collaborated with Geola Digital UAB and with Yves and Phillippe Gentet to create holograms of each of the sculptural drawings created in VR.

The holograms printed by Geola measure 15 x 15 cm and are achromatic single parallax surface relief digital holograms with a hogel size of 100 microns. They are printed on glass (coated with photoresist) using a DWDH transmission hologram printer which employs a blue pulsed laser. These holograms can be replayed with either one or two LEDs. The advantage of using 2 LEDs is that this increases the angle from which the drawing appears to be black & white at the same time as increasing brightness. Outside this angle, the appearance is that of a rainbow hologram. The particularity of this type of hologram is that it can be viewed from both sides (in transmission as well as in reflection).

Figure 9. Surface relief digital holograms of Empress Min (left) and Yu Gwan Sun (right) printed and framed by Geola

The hologram of Empress Min printed by Yves and Phillippe Gentet using the Chimera technique is full parallax with a hogel size of 250 microns and measures 30 x 40 cm. The hologram of Yu Gwan Sun is single parallax and measures 10 x 13 cm. Both are replayed with single RGB LEDs. The beauty of full parallax holograms is that the image is very stable and does not distort as you move around to see it from different angles. It is also a more accurate representation of the VR sculptural drawing.

Figure 10. Chimera holograms of Empress Min (left) and Yu Gwan Sun (right) printed byYves and Phillipe Gentet.

3.2 Marna (2022)

The VR hologram that I created for the Marna installation embodies this building in two stages of its life - as it looked before the roof and windows collapsed due to a fire in the 90's, and as the ruin that it became afterwards. Behind the hologram and visible through it, is the second part of the installation, a giclee print made from a large ink drawing (84 x 89 cm) depicting the new office building that was erected on the ground of the old cinema building. And thirdly, the original ink drawing, which was made on 9 A4 sheets of paper, mounted directly on the wall to the left of the hologram, in a disorderly grid.

Figure 11. A view of the installation 'Marna' from the exhibition 'The City Vanishes' (2022) at Annart Gallery, Bucharest.

The post processing method used after completing the work in Tilt Brush is different from my other similar projects. Because the scene contained numerous repetitive elements (i.e. the windows and other architectural elements) and also because the Tilt Brush interface makes it difficult to align objects at precise angles, I decided to only draw individual elements in Tilt Brush and then multiply and assemble them in Blender. The image data sent to Geola was also different in the sense that, as mentioned above, it contained two different stages of the building (for a 2-channel hologram). When seen from a frontal view, the windows and dome are visible, but as you move towards the edges of the field of view, they disappear.

Figure 12. Two views of the hologram ‘Marna’ showing the two channels.

Whenever I employ holography as an artistic medium I strive to give as much importance as possible to what Jaques Desbiens calls ‘the dispositif of holography’. Desbiens suggests that the true nature of a hologram is neither physically nor visibly present in the artwork but is instantiated by the meeting of the work with the viewer and the replay light [12]. This brings into focus display-related issues and the question of how to optimize the presentation of the artwork.

This concern is particularly evident in ‘Marna’ (the other two projects presented here are very recent and have not yet been publicly displayed) and it is reflected in a number of choices made throughout the development of the project: selecting the VR artmaking and postprocessing tools most suited to be visualised through holography, identifying surface relief digital holography as the best type of holographic technique in terms of visual and archival quality, displaying the hologram in a custom made double-sided frame, illuminating it with projectors to reduce the amount of light cast outside the hologram, and making the hologram share space with an equally striking, powerful image made in a different medium. The aim of this optimisation of visual quality was to create an ideal encounter between artwork and viewer, where medium specificity becomes secondary. Thus, paradoxically, by minimising the character of holography or, in other words, by allowing the viewers to forget that they are looking at a hologram, the story of the building constituting the subject was allowed to take the leading role and thus to establish a dialogue with the viewer undistracted by the quirks of the medium.

4. CONCLUSIONS

The main goal of these projects was to use holography and its qualities to frame the striking stories behind each of the artworks presented.

The holographic renderings of Empress Min and Yu Gwan Sun serve not only as portals into pivotal moments of Korean history, but also as universal symbols, echoing comparable struggles that resonate across all cultures. These sculptural drawings, imbued with historical significance, engage viewers on a broader spectrum, underscoring the universal nature of these narratives and their prevalence throughout global cultures.

The Marna installation constitutes a reconciliation of past and present which sometimes only seems to be possible in the imagination or in the realm of art. I used the medium of holography to bring back into existence that which no longer is, while at the same time expressing its frailty and ephemerality in contrast with the more robust body of the print that dominates the exhibition space. The fractured original drawing is meant as a projection of the future, which, although uncertain, is bound to bring the disintegration of even the steadiest, most solid of manmade structures.

Holography's ability to give tangible form to absence while at the same time expressing fragility through the disappearance of the holographic image outside the angle of view provided the perfect medium for telling these stories. Each artwork presented here focuses on a historical subject, which, in addition to making use of holography's mimetic, representational function, is used as an anchor for storytelling. The chosen subjects all have unsettling stories behind them, yet these are stories that need to be kept alive. Just as, when outside of our focus, the holographic image seems to disappear, similarly these stories rely on our gaze and privileged position to continue to live on.

ACKNOWLEDGEMENTS

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Coherently breaking rules for light's sake: a condensation of a few decades recording argon lit dcg

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Light Foundry

Abstract

A brief excursion into the meaning of light, the implications for the ever-expanding use of the terms of holography, how the techniques of ammonium dichromate gelatin allow great freedoms for artist expression in general, and for the author in particular. For example, the ability to mix our own emulsion allows us to create plates fine-tuned for each project, in size, and with the color range in mind. The flexibility of the emulsion means something glorious can emerge from mishap or experimentation, and bright images shine where the textbook says there should be nothing. Learning to understand the realm of the photon is satisfying and good.

Paper

the beauty of argon light
using lightbulbs as the object
getting bored with spacial filters
Neils Abramson ellipse of coherent length
ipad/iphone as reference beam
opal as photonics crystal, opal as object mirror
meteorite as reference mirror

The movie The Magic Lantern showed the exhibition of a brand new technology, film shuttered through a projector, to an expectant crowd. Reflected off the theatre wall, light showed a moving picture of a train clearly heading towards the seated audience, and frightened them so, that many ran for the doors to escape. Because they've just seen an illusion of mass in motion.
Illusion is powerful, it can inspire people.

In my early years of college I saw an exhibit, a collection of holography, at a gallery at the University of Texas in Austin.
It was a very dark room filled with transmission holograms, real light suspended in space; that exhibit really changed my life forever and I sought to find a place to learn how to do whatever was happening there.
Eight years later, I found that university and was making all the rudimentary types of holograms in silver halide lit by helium-neon. Completely missed the 1985 symposium, then attended workshops at Lake Forest in 1986 and 87 working under Tung Jeong, who taught us how to make these amazing things, and for whom I will be eternally grateful.

And by 1988 my first symposium at Lake Forest. There I found a cohort, like you gathered here today, a group of people with a common interest and discipline and knowledge, (and with a playful and creative streak)

Before my first symposium I pondered the relationship between the reference beam and the object; I thought about what was truly happening, about pulsed laser, and keeping exposure times short to minimize movement, so I thought about how easy it might be to make a handheld hologram with an helium-neon laser, and it truly is easy!

Then the discovery of Augie Muth's studio, the Light Foundry, where I learned to discard many of the strictures I thought were inherent to holography.

Rigor and the specifics of film mounts and glass plate; all the rigor that holography inherited from the study of optics; that the plane of the laser beams must be parallel to the optical table, the beam lengths from the beam splitter must be exactly the same, you've got to use a spatial filter, the room has to be completely dark, etc.
None of those are necessary.

What is necessary? stillness, ok—patience as well, a happy laser, at least two different wavefronts of coherent light headed toward a crossing, a photosensitive medium placed in that crossing to make them interfere.

While I learned the discipline of the spacial filter, it was richly rewarding to discover that an iPhone, or iPad, or slice of meteorite makes a wonderful reference mirror, that the patterns arising from the path of a laser through glass, light bulbs, screwdriver handles and opals make intriguing object beams, as do metal plates, flower petals and forest leaves make good objects, and that optical mounts can lay on their side on the table just fine.
Shadow plays an essential part.

Of course I enjoyed the many illusions of 3D all around us.
Yet more and more I understood that my attraction is to light itself, and the way it interacts with the world, the way it refracts and reflects into our eye, and how we apprehend light.

All my work is the physical materialization of light played back by new light, recreating the singular event of exposure as a whole image.
Like photography's decisive moment, they are recordings of the truth of light in that moment.

The word hologram is a strongly misused word within our culture.

The confusion runs as deep as the difference between truth and illusion.
Just like many other holographers, my work is real. It is material light refocused within the sphere of human experience. It is built by recording waves of a single color of light, waves interacting with each other, and viewed as one entity of light and color. Completely analog, a continuous experience of light.

The illusions are commonplace. Some are extraordinary, legendary; Princess Leah garnered her only hope through a cinematic special effect. Many are mundane; when deceased celebrities appear on stage, it is through a Vaudeville illusion called a Pepper's Ghost, a trick of the eye lit by limelight, a trick that predates radio, that predates the lightbulb !
And when news anchors appear as if ghostly in a broadcast, it is via a video effect. It is not real.
Hologram…Hologram…Hologram…Hologram….
All these are only illusions

These illusions all label themselves as holograms falsely.

Even this famous work, The Kiss, is a hologram only in the sense that this picture of a city is a building, and this picture of a crowd is a person.

From this, you might think I care about the word hologram.
I don’t. I am leaving it behind, except for times I’m around people who know the secret handshake. Like you guys here today!
I am sad that it’s been so smeared and misconstrued, sad to see all the multimundane displays of illusion, wearing an ill-fitting ‘hologram ’suit of clothes.
Perhaps the word is poisoned forever, but my desire is to leave out that word entirely when I speak of my work.
I will speak of the wondrousness of light, of the magic of the laser, of how light talks to other light.
I will say that it’s a recording of a conversion within and between light, I may admit to using holographic techniques.

So, what is the nature of the work? There’s a nanoterrain of structural undulation within the thickness of the DCG emulsion, just like every other recording medium used in holography. Structural color occurs throughout nature.
What all of us do here is make schemochromes.

I know that all the wholehearted amongst you know that the more time we spend in this discipline, the more love and appreciation we have for light and perhaps the more desire we feel: to understand the photon, to understand how the photon moves and interacts, to understand the realm of the photon.
And understanding the realm of the photon with your whole heart and your whole brain, and openness to the world, will lead you to make more wonderful works in light.
It is a way to integrate our love of science and our love of being a full hearted, human organism; aware, and bathed in light.

What we are making is structural color.

It is the wing of the butterfly
It is the back of a beetle
It is schemochrome

It is the most natural thing in the world

Rediscovering beauty: A photographic journey through the albumen Lippmann process

Filipe da Veiga Ventura
Silverbox

ABSTRACT

This paper chronicles a nine-year journey through the exploration and refinement of the albumen variant of Lippmann photography. The narrative focuses on the challenges of rediscovering the albumen process and achieving results without Mercury, instead using a 4% emulsion-air interface reflection. Guided and inspired by the work of Dr. Robert Neuhauss, the author interweaves empirical science and artistic expression, offering a testament to the synergy of artistic exploration and scientific discovery in the realm of photography.

BODY

In 2014, I embarked on a unique adventure into the realm of Lippmann photography. A chance discovery on a holography forum section dedicated to Lippmann photography led me to the albumen variant of the Lippmann process. Intrigued by the possibility of achieving results without Mercury I dove into this exploration.
My journey began with immediate success using holographic panchromatic plates and Lumiere's pyro developer with the sole purpose of witnessing this marvelous phenomena. This early triumph was encouraging, but the real challenge lay ahead: rediscovering the albumen process, a journey marked by an initial high rate of failure and serendipitous moments of success.
Over the course of nine years, I produced countless albumen plates through a rigorous trial and error process. I learned the pivotal role that egg quality plays in the process and the vast quantity of known and unknown variables. The decision to opt for a 4% emulsion-air interface, as an alternative to Mercury due to safety reasons, resulted in a much smaller fringe contrast, making it more challenging to achieve bright and saturated results.

Despite these challenges, and by gradually developing my own method, I have managed to increase my success rate over time to about 80%. However, the process remains unpredictable and continues to surprise me, keeping the journey exciting and challenging.

Simultaneously, I began to use the process in my artistic work. My images embody my search for colors and brightness, and the acceptance of failure. Each photograph stands as a testament to the fusion of photography and empirical science.

Through this long-standing engagement with the process, I've gained deep insights into its challenges and artifacts of this magnificent process. I've developed a profound appreciation for the work of historical practitioners, particularly Dr. Robert Neuhauss. As a result, I have devised a straightforward albumen process that allows me to create Lippmann plates from raw materials in under two hours, using minimal lab equipment. What could be more exciting than quickly making interferential color photography at home with eggs and silver?

My journey through the world of Lippmann photography is a testament to the synergy of art and science, curiosity and perseverance. Through years of failures and successes, I have tried to redefine the boundaries of this process, contributing to a rich tradition of photographic exploration and scientific discovery.

The passion for Lippmann photography, with its many possibilities and variables, continues to captivate me. Like Dr. Robert Neuhauss, who was still creating emulsions right before his death, I foresee a lifelong engagement with this process. My journey continues, and with it, the promise of more discoveries and artistic creations.


First successful albumen Lippmann plate 2014

Royal - 2023

Flooring memory -2022

Clockwork -2018


Vegetables

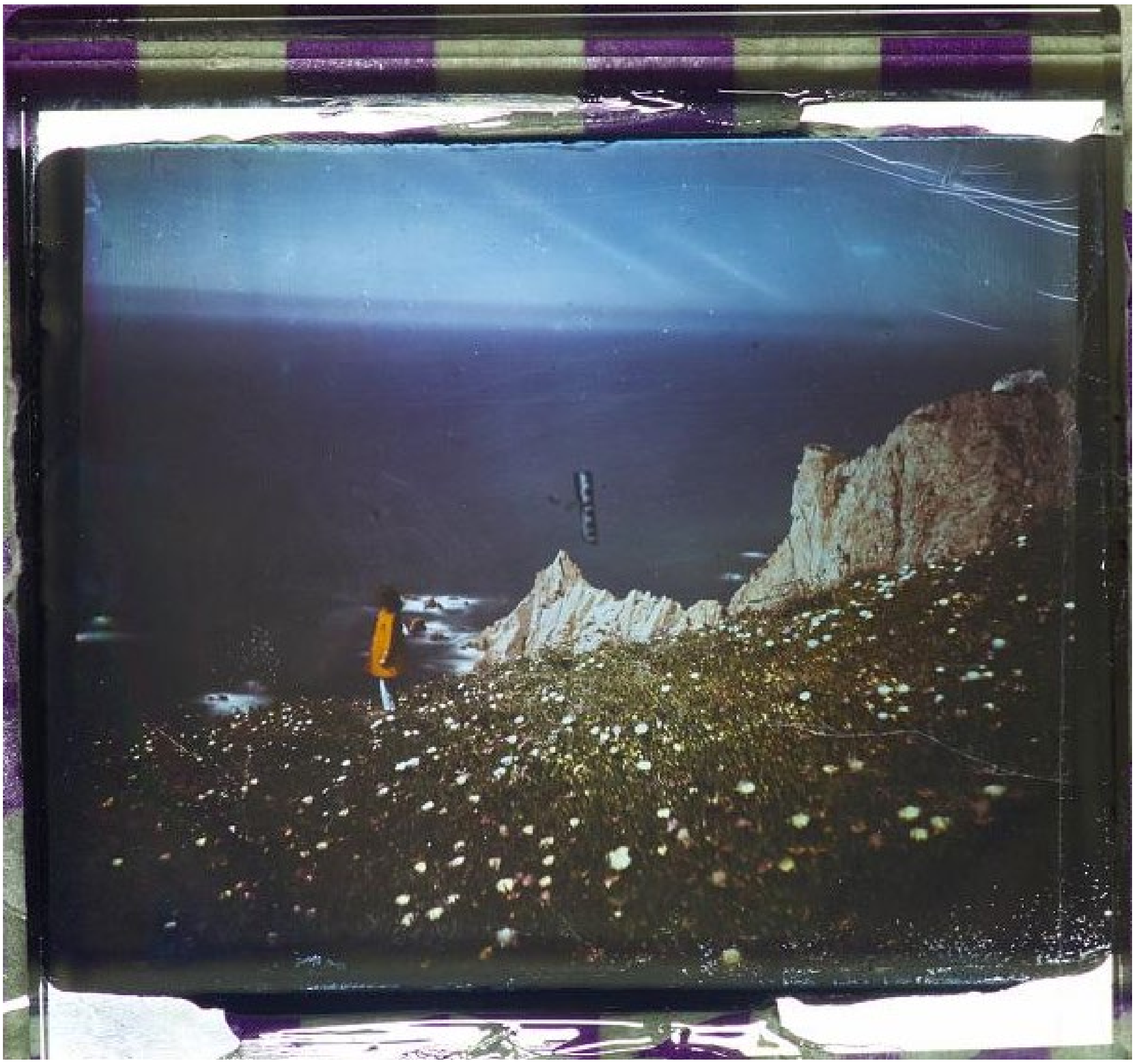

Dragon and Orbs - 2022

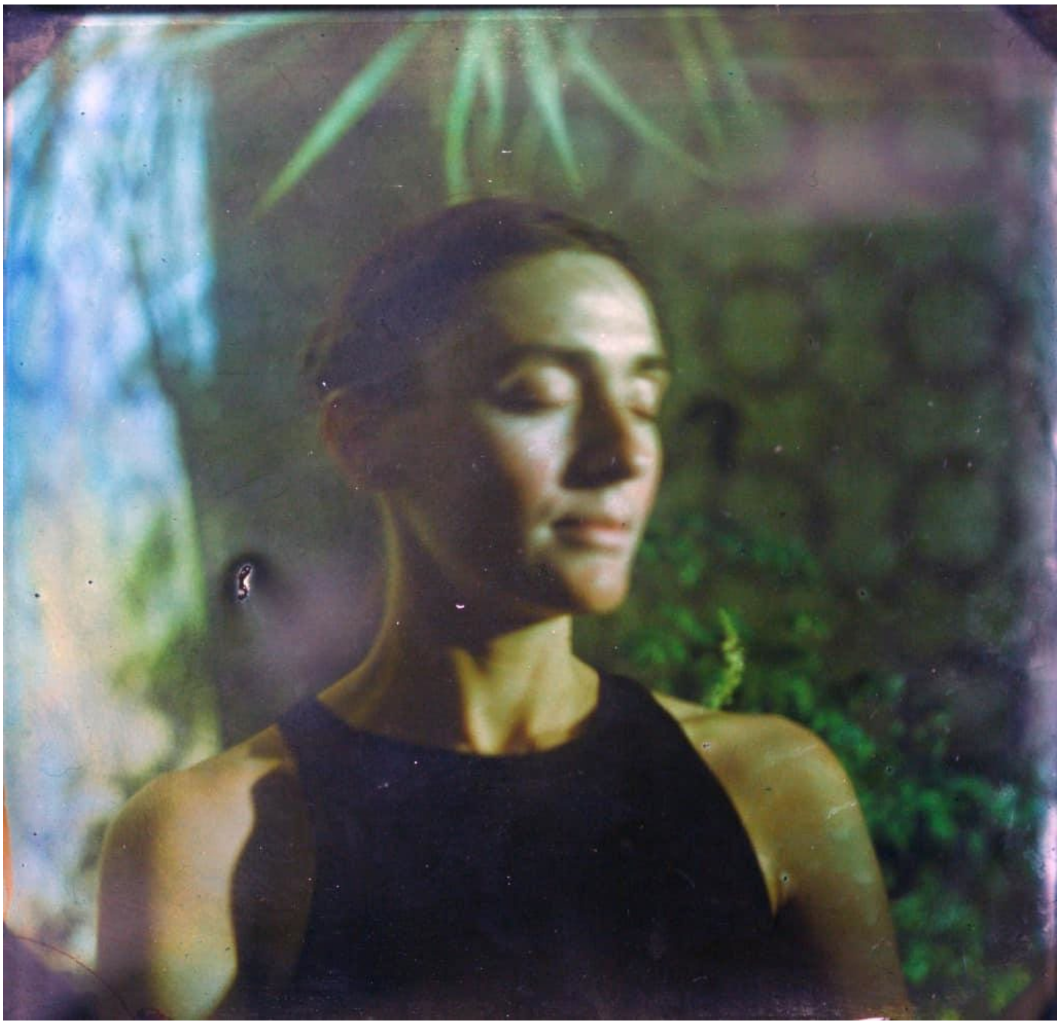
Ingredients -2022

Plastic parrot and books - 2021


The three orbs -2022


silverbox





How to make CHIMERA hologram with unreal engine

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ABSTRACT

CHIMERA is the third generation of digital holographic printing system based on three low-power continuous lasers combined with Ultimate U04 silver-halide holographic glass plates. This paper discusses how to quickly and easily create content for CHIMERA holograms with Unreal Engine software.

Keywords: Digital hologram, CHIMERA, silver-halide, Unreal Engine.

1. INTRODUCTION

In 2019, the third generation of holoprinter called CHIMERA[1] by Gentet et al is based on three low power red, green, and blue continuous lasers combined with the silver-halide material ultimate U04[2], and prints digital holograms with a 50 Hz speed, a 120◦ full-parallax and a hogel resolution of 250 µm. The recording of a CHIMERA requires the prior acquisition of a series of perspective images—points of view of the 3D scene. For a half-parallax hologram up to 768 horizontal images are recorded on a 120-degree arc of a circle and for a full-parallax, the procedure is repeated up to 192 different levels of elevation, creating a cylinder of points of view as shown in Fig. 1 for a total of 147456 images.

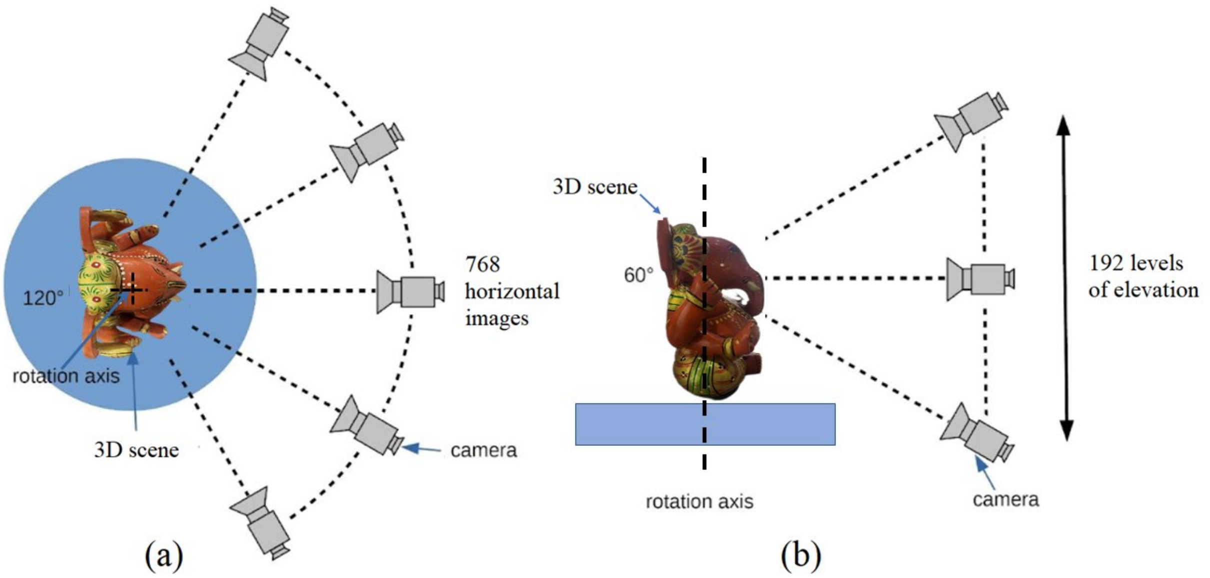

Figure 1. CHIMERA recording procedure.

For 3D CG modeling CHIMERA holograms were usually created with 3D computer graphics program such as 3ds Max software[3], Blender or Maya but the rendering of each image was very slow'.
Working at real time, game engines offer a better solution. Unreal Engine[4] is the most famous and powerful game engine of the moment. It is free and freely available. This study shows how to use Unreal Engine to create perspectives images and content for CHIMERA hologram with different ready-to-use OBJ files models. Table 1 presents the list of features of Unreal Engine vs 3ds Max. Figure 2 compares the calculation speed difference between Unreal Engine and 3DSmax.

Table 1. List of features (Unreal Engine vs 3DSmax).

Unreal Engine	3DS MAX
Real time engine	Render engine
Vray, RayTracing nvidia, UE light	Vray, 3DSmax light
.obj, .fbx, .gltf, .glb, .usdf files	.fbx, .max files
Large free market place	Autodesk app store
Free and open source	$ 1,785/ year

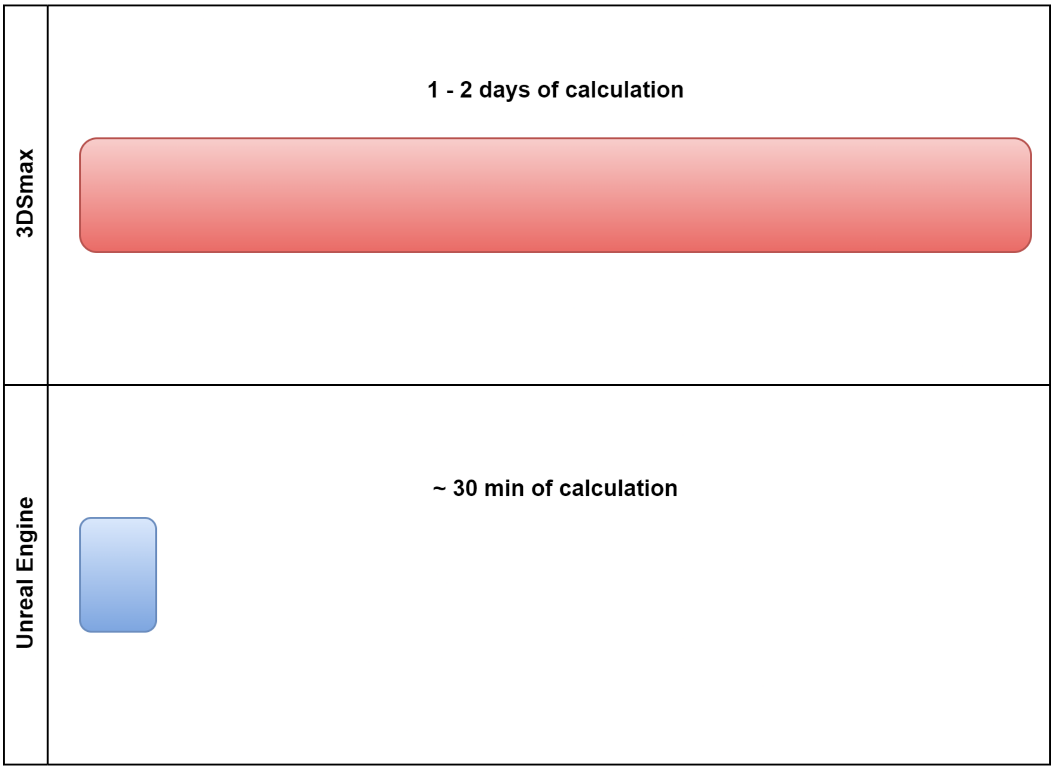

Figure 2. 660×880 pixels Calculation speed (Unreal Engine vs 3DSmax)

2. Materials and methods

2.1 Computer configuration

To use the Unreal Engine, the minimum configuration for your computer is Windows 7 64-bit, 64-GB RAM, 256GB SSD (OS drive),2TB SSD drive, NVIDIA GeForce GTX 970.

2.2 Method to create content with Unreal Engine

2.3 Import 3D model

The best formats are glTF, usd, fbx or glb. Fig 3. shows how to progress a 3D model files into Unreal Engine

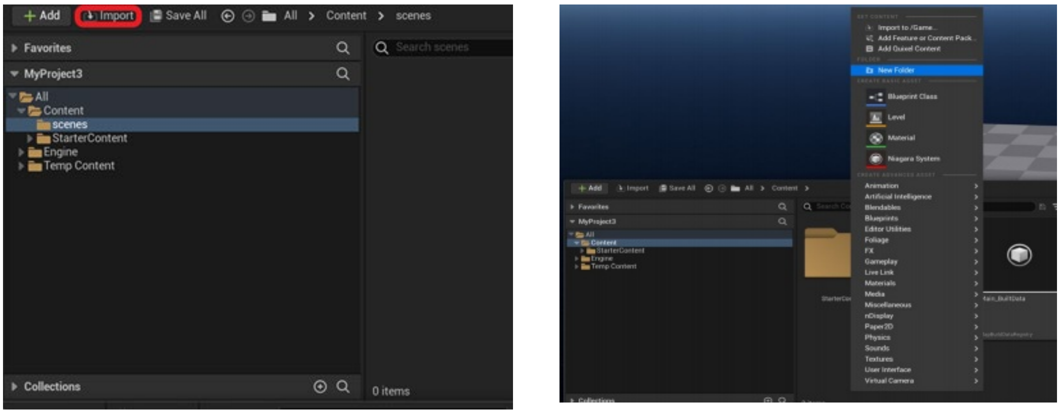

Figure 3. How to Import 3D model (Unreal Engine)

2.4resize or modify your 3D model

drag and drop 3D model on the scene, model appears larger; 3D model need (sometimes) to reduce this size. To do this, select 3D model in the Outliner (top right interface) and go to Transform and Scale. Change the scale value to something smaller (like 0,1) for all axes and set the location to zero like the fig4.

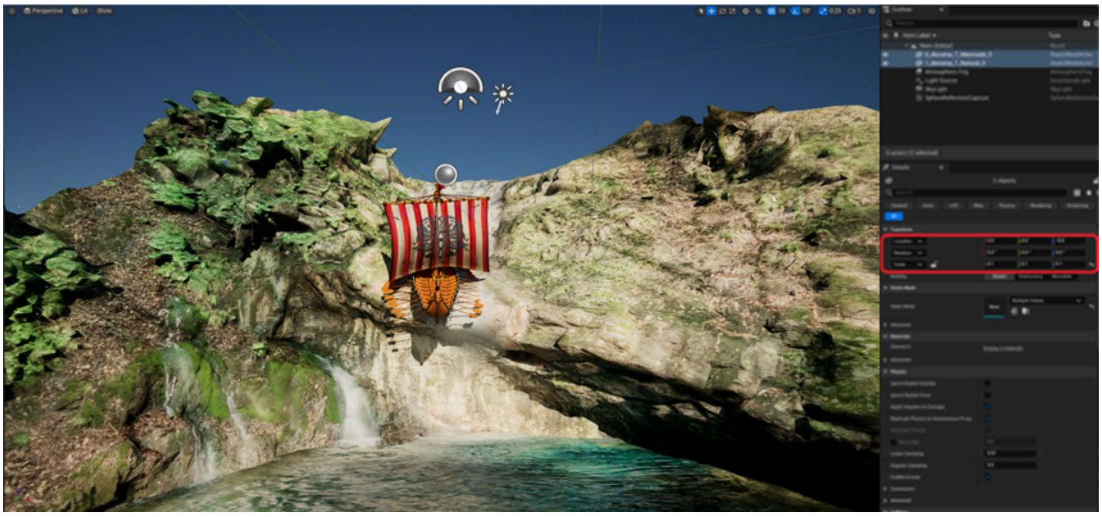

Figure 4. resize or modify (Unreal Engine)

2.5 Use the scanner script

To open the scanner script, go to the scanner folder in the content drawer and select the "ScanningProcess_30x40". Normally two cameras appear "cineCameraActor" is the camera that will record the scene and “cineCameraActor3" is the camera that manage scene. check the position of the two cameras through Fig 5.

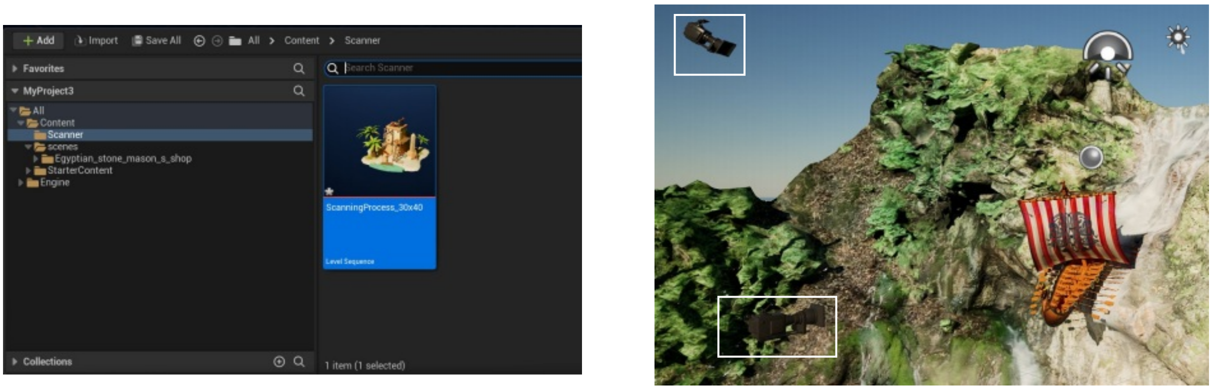

Figure 5. Unreal Engine script cameras

Now let's readjust 3D model (resize, move), this view represents the front (zero position) of final hologram. Fig 6. shows the incorrect and correct positions of the 3d model.

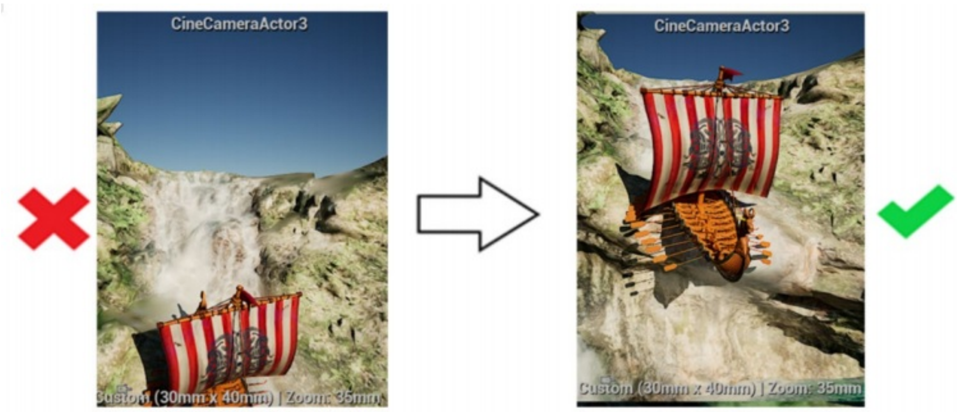

Figure 6. incorrect and correct positions (Unreal Engine)

procedure, the camera may move by mistake, be sure to always adjust the settings as the images below. fig 7. it is possible to change things such as the size, angle, and position of the 3d model by entering numbers.

Figure 7. Location, rotation, scale screen (Unreal Engine)

satisfied with front view, modeling need to adjust the depth of hologram. To do this, select in the Outliner "CineCameraActor3" and go to "Focus Settings" and select "Draw Debug Focus Plane".

This plane represents the plane of the final hologram, everything behind this plane will be inside the hologram and everything above this plane will float outside the hologram. which is shown in Fig. 8.

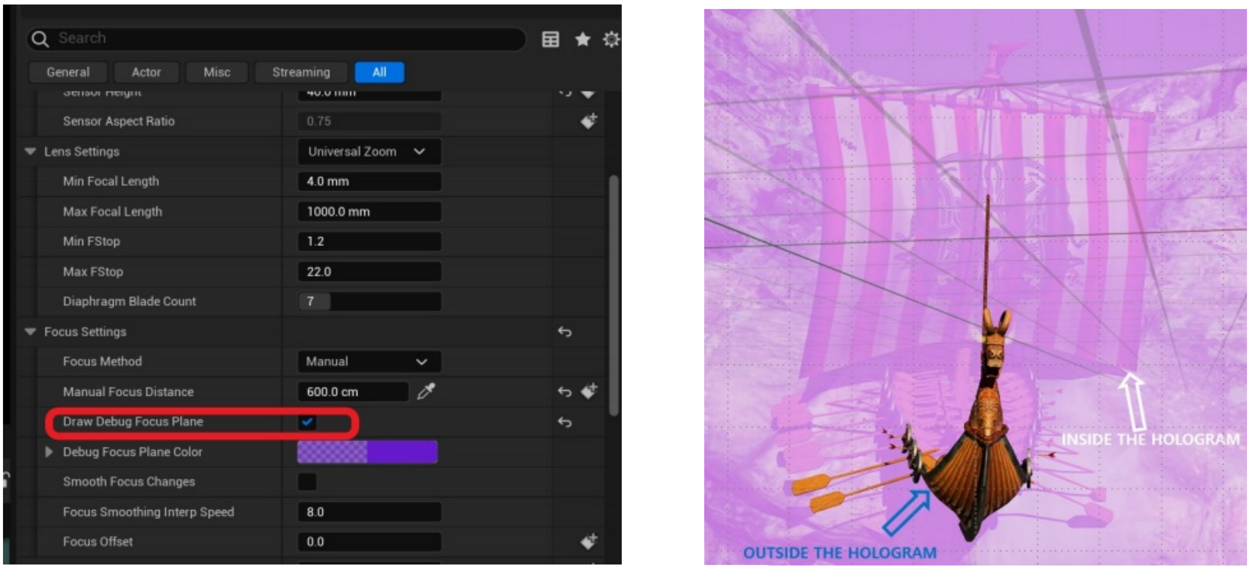

Figure 8. The inside and outside position (Unreal Engine)

2.6 Launch the scanner script

Go to the sequencer panel to launch the script. Go to the "Render Movie" option and select "Movie Scene”

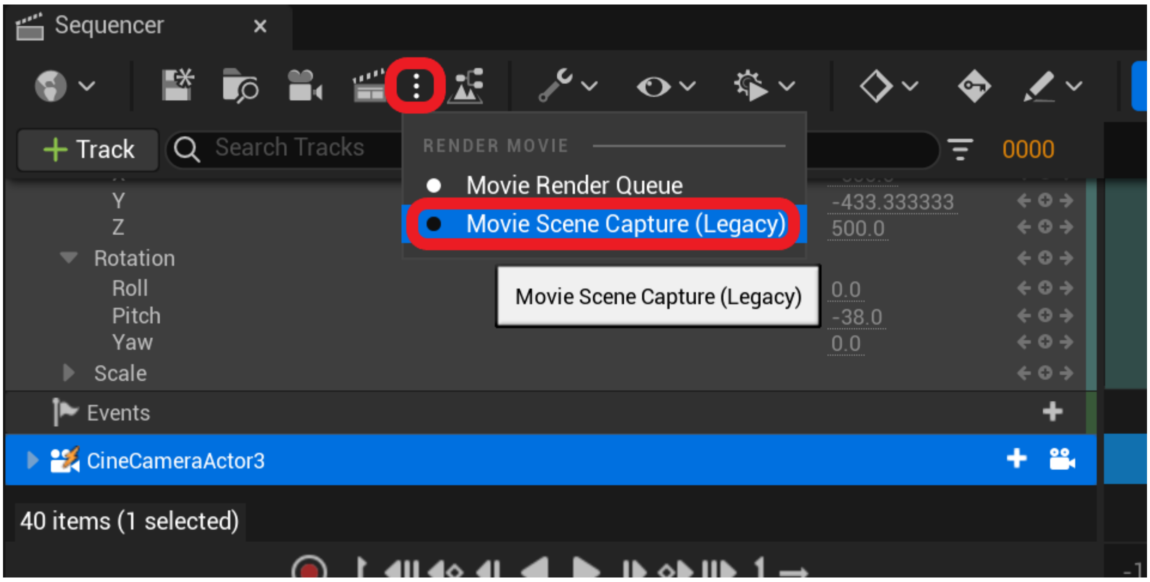

Figure 9. Capture (Legacy)"

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After do this, go to Render Movie Settings and modify, like the images below, the information of the Image Output Format, Resolution and Output directory. And start ‘Capture movie’. As shown in Figure 9.

3. RESULTS

The Unreal Engine creates colorful modeling in a shorter time than any other modeling programs, and the rendering speed is also very fast, so it works best with digital holograms. Fig. 10. shows a digital hologram made with Unreal Engine

Figure 10. Result of hologram (Unreal Engine)

4. CONCLUSION

Unreal Engine offers a new, simpler, and faster method for creating more realistic and complex contents for CHIMERA digital holograms. This method is envisaged to allow the widespread dissemination of display holography. Acknowledgement

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Making holograms with IPhone

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ABSTRACT

Holograms are becoming more popular and digital holography allows to create new content from digital cameras. Modern smartphones such as the Iphone include algorithms for intelligent image segmentation and can record depth information. The purpose of this presentation is to show how these technologies can be used to produce content for digital holograms. This paper presents a detailed workflow for creating digital holograms using an iPhone. By leveraging the capabilities of the High-Efficiency Image Format (HEIF) and 3D software, this workflow allows users to transform a simple photograph into a captivating and immersive holographic representation. The proposed method encompasses several sequential steps, including HEIF file processing, image extraction, retouching and beautification, 3D mesh creation, lighting and effects adjustment, camera rig construction, and rendering techniques for both half and full parallax holograms. The paper concludes by discussing the advantages of this workflow in facilitating the creation of new content for holography.

Keywords: hologram, HEIF, portrait, depth map, Iphone

1. INTRODUCTION

The field of holography has seen significant advancements in recent years, enabling the creation of stunning three-dimensional representations. Traditionally, analogue holography as described by Gabor[1] required complex optical setups and specialized equipment. Analog holograms are created using optical techniques[2], where interference patterns are recorded directly on light-sensitive materials like photographic film. These holograms capture the full wavefront information of the object, resulting in high-resolution and continuous-tone representations. In contrast, digital hogel-based holograms[3] rely on digital display technologies, where an array of pixels or hogel elements serve as the building blocks of the hologram. The digital hogel-based holography allows many new ways of creating impressive three dimensional content that can be printed by a hologram printer. One such method is holostereosynthesis, introduced by Gentet et al. In 2022[4]. This method combined in a single digital CHIMERA hologram [5] several photographs of the same subject recorded with a progressive shift in focus to reconstruct a portrait in 3D.
With the widespread adoption of smartphones equipped with advanced depth-sensing cameras[6], such as the iPhone, new possibilities have emerged for creating holograms with accessible technology. This paper introduces a comprehensive method that harnesses the power of the High Efficiency Image File Format (HEIF)[7] format and 3D software to produce digital holograms. The workflow involves multiple stages, ranging from initial image capture to final rendering, and opens up avenues for creativity and content generation in holography.

2. METHOD

This section describes the workflow from image capture until the final rendering. Figure 1 shows an overview of the process that will be described in detail.

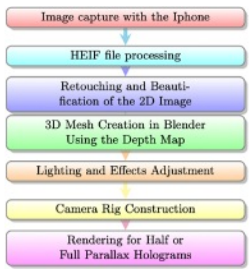

Figure 1. Workflow overview

2.1 Image capture with the Iphone

The iPhone utilizes LIDAR (Light Detection and Ranging) technology to capture depth information[8]. LIDAR emits laser pulses and measures the time it takes for the laser to bounce back after hitting objects in the scene, enabling accurate distance measurement. The iPhone's LIDAR sensor emits laser beams and calculates the time-of-flight to create a depth map. This depth map represents the varying distances of objects within the scene[9]. By combining the depth map with image data captured by the iPhone's camera, a comprehensive representation of the scene is obtained, enabling advanced computational photography techniques and applications such as augmented reality, portrait mode, and depth-based effects. The integration of LIDAR and depth maps in the iPhone enhances the accuracy and versatility of depth sensing capabilities.

2.2 HEIF File Processing:

To capture the necessary data for hologram creation, the iPhone's HEIF format is utilized. Besides Image Information the HEIF format contains additional information such as the depth-map, separate highlights that can be used for high dynamic range (HDR) imaging[10] as well as segmentation and hair information that can be used in a wide range of applications for image processing. For the purpose of the creation of a digital hogel-based hologram two image elements are extracted from the HEIF container: The 2D image and the depth-map. Figure 2 shows the image and its depth-map as recorded by the Iphone and scaled to the same dimensions.

a) 2D image	b) depth map

Figure 2. Portrait image recorded by Iphone.

2.3 Retouching and Beautification of the 2D Image

To enhance the visual quality of the hologram, the 2D image extracted from the HEIF format undergoes retouching and beautification. This can be achieved by the application of artificial intelligence algorithms[11] or image manipulation tools, such as GIMP[12], to refine the image. Techniques such as noise reduction, color correction, and sharpening are employed to optimize the appearance of the portrait.

2.4 3D Mesh Creation in Blender Using the Depth Map

The next step involves translating the 2D image into a three-dimensional mesh using the 3D software Blender[13]. Blender is a powerful open-source 3D creation software used for modeling, animation, rendering, and compositing. It offers a comprehensive set of tools and features for creating high-quality visual content. With Blender, users can build complex 3D scenes, characters, and objects, utilizing a wide range of modeling techniques such as polygonal modeling, sculpting, and procedural modeling.

The depth map extracted from the HEIF format plays a crucial role in this process. The 2D image is imported as a plane in Blender. A displacement modifier that utilizes the depth data to generate a textured 3D mesh. Parameters in the constraint allow control of the depth and to smoothen the depth map according to the desired effect. The 2D image provides the texture for surface created by the transformation. The mesh is positioned at the origin of the scene, ready for further refinement and manipulation. Figure 2 shows the transformed mesh inside the Blender workspace.

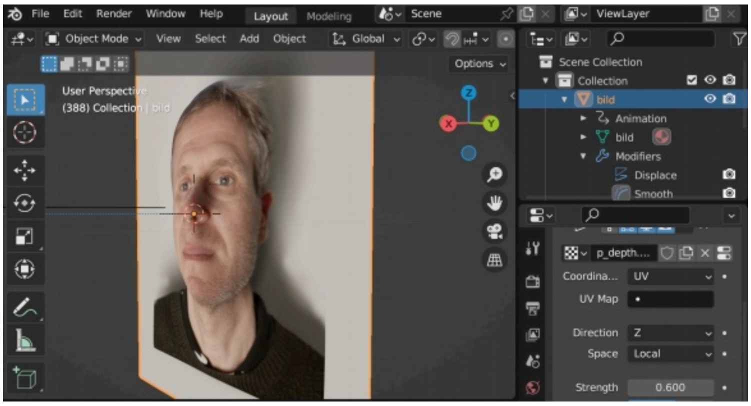

Figure 3 Mesh in Blender Workspace

2.5 Lighting and Effects Adjustment:

Creating an appealing and visually captivating hologram requires careful consideration of lighting and effects. Various techniques can be used to illuminate the holographic scene within Blender[14]. The adjustment of lighting settings, such as directional lights and ambient occlusion allow to increase the artistic value of the portrait. The three-dimensional model recreated using the depth map allow to modify lighting and shadows of the original image.

2.6 Camera Rig Construction:

In order to create the digital hogel-based hologram a multitude of single viewpoint images is needed. For this purpose a virtual camera rig is constructed within Blender[15]. The camera rig is placed at a predefined distance from the center of the 3D mesh. The distance corresponds to the viewing distance of the finished hologram. In Blender constraints are applied to the camera, enabling it to rotate around the mesh at an angle of 120 degrees, simulating the desired viewing angle in the final hologram. Another constraint ensures that the camera remains targeted at the center of the mesh, which corresponds to the position of the hologram plane. Figure 4 shows the shematic overview of the virtual camera rig.

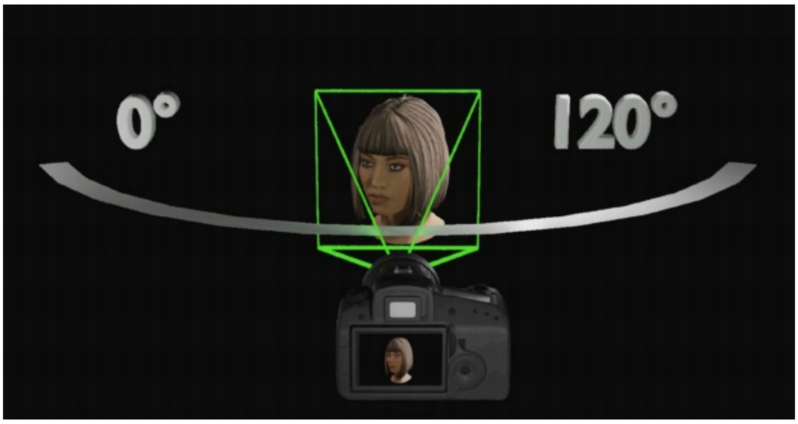

Fig. 4. Virtual Camera Rig in Blender

2.7 Rendering Techniques for Half Parallax Holograms:

A half parallax hologram is a type of holographic display that provides a limited viewing angle in the horizontal direction. It typically consists of a series of frames captured from different perspectives around a central object[16]. When viewing the hologram, the observer experiences a 3D effect as they move horizontally, revealing different aspects of the object. However, the vertical viewing angle remains fixed, offering a constrained depth perception. Half parallax holograms are commonly used in applications such as holographic portraits, product displays, and artistic presentations, where a moderate level of depth is desired without requiring a full 360-degree viewing capability.
To generate a half parallax hologram. The camera's rotation is divided into a specific number of frames, such as 768 frames, capturing different horizontal perspectives of the holographic scene. Each rendered frame is saved as a separate image file, which will be used in the final holographic representation. These separate horizontal view points are used to calculate the hogels that will constitute the half parallax hologram.

2.8 Rendering Techniques for Full Parallax Holograms:

A full parallax hologram is a type of holographic display that offers a complete and immersive 3D viewing experience from all angles. Unlike half parallax holograms, full parallax holograms provide a wide range of viewing perspectives, including both horizontal and vertical movement. This allows viewers to see the holographic object from different angles, revealing its depth and spatial details. Full parallax holograms create a realistic and dynamic representation of the original object, enabling a more comprehensive and engaging visual experience. They are often used in applications such as medical imaging, engineering design, and scientific visualization, where accurate and detailed 3D information is crucial. To achieve a full parallax hologram, the workflow is extended to create a vertical viewing angle. The camera is moved stepwise from the top to the bottom of the holographic scene, capturing one row of half parallax holograms after another. This process ensures the full coverage of the portrait scene providing all necessary perspective viewpoints to calculate the hogels of a full parallax hologram.

3. RESULTS

The result of this workflow provides the necessary multi-viewpoint data to perform the necessary calculations of hogels that are the base of the digital half or full parallax hologram generated with a modern hogel-based hologram CHIMERA printer. Hogels were generated and recorded with a 250 μm resolution one after another into 11×15 cm U04 holographic plate[17]. When the CHIMERA was illuminated a fine color and half-parallax reconstruction of the portrait in 3D was generated, as shown in Fig. 5.

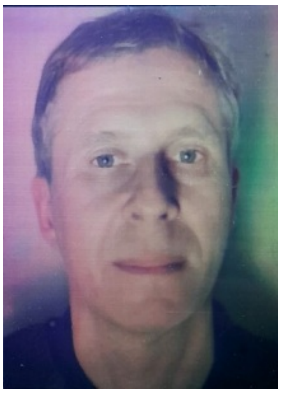

Fig. 5. CHIMERA holographic portrait.

Although the reconstruction is not perfect, with the portrait appearing slightly like a bas-relief, the overall 3D effect is quite realistic.

4. FURTHER RESEARCH

All depth based 3D representations encounter limitations that can be caused by occlusions[18] that may occur from certain viewpoints. The HEIF format contains intelligent segmentation information about hair, glasses, and skin tones which can be used to overcome these limitations and are often used in mobile image manipulation apps. Including these in the workflow would be beyond the scope of this paper and can be subject of further research.

5. CONCLUSION:

The proposed workflow for creating digital holograms with an iPhone offers numerous advantages in the realm of holography. By leveraging the HEIF format and 3D software, users can transform ordinary photographs into captivating and immersive holographic representations. This workflow provides accessibility, convenience, and flexibility for content creators, enabling them to explore new dimensions in holography without the need for specialized equipment or extensive technical knowledge. Furthermore, the integration of artificial intelligence, image manipulation, and 3D software empowers users to push the boundaries of creativity and generate unique holographic content. The workflow presented in this paper represents a significant step towards democratizing holography and opening up exciting possibilities for future applications in various fields.

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Holography at the science festival: engaging audiences with art and scientific research

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ABSTRACT

This paper presents a case study on the use of holographic artwork and display holography to engage public audiences with current research in Physics and Astronomy. While display holography successfully captures the attention of audiences and makes the research more accessible, it can also produce a barrier to conveying the scientific background of the research it seeks to communicate. In this study, we examine the use of holography as a vehicle to engage audiences with Black Hole, String Theory and X-Ray Crystallography research at the University of Southampton's Science and Engineering Festival in 2022 and 2023. Through this case study, we explore the ways in which audience engagement and understanding can be enhanced through the effective use of art and holography as a tool for science communication in the context of cutting-edge research. The findings of this research have wider implications for engaging audiences with complex scientific theories and can help to promote a greater appreciation of the interconnectedness between art and science.

Keywords: Public Engagement with Research, Sci Art, Art and Science, Science Communication, Art Holography

1. INTRODUCTION

Science festivals and Photonics campaigns are well-established cultural events in Europe, providing a platform for scientists to showcase their research to a science-interested public. It is becoming increasingly common for funding bodies to encourage scientists to work with artists by offering grants for collaboration because it is thought that working with artists will enable scientists to reach new audiences. For example, the IOP's Public Engagement Grants include funding for work with artists and the public[1]. However, might there be instances when using artwork to engage with scientific research hinders science communication by detracting audience's attention away from the research to focus on the art? To answer this question, I will describe the use of holography to engage audiences with Astrophysics, String Theory and X-Ray Crystallography research at The University of Southampton's Science and Engineering Festival (SOTSEF) in 2022 and 2023. Firstly, the paper will firstly describe the context for the study, next provide a brief description of the scientific research that the holographic activities were used to engage audiences with, then outline the holographic artwork, and a description of the methods for science communication that the project undertook. The paper will include an analysis of an interview undertaken with a science communicator completed as part of an evaluation of the project, and conclude with recommendations for others who may be considering using holographic artwork and demonstrations to engage the public with science.

2. CONTEXT

SOTSEF is the University of Southampton's award-winning annual science festival that highlights University research, facilities, and the communications skills of staff and students, to approximately 4,000 visitors. The event includes over 100 stands, facilities tours, and lectures and involves 100s of members of staff and student volunteers. While the focus is on science and engineering the festival encourages engagement through the arts:

> *"Over the years, Science and Engineering Festival has developed into a STEAM (Science-Technology-Engineering-Arts-Mathematics and Medicine) festival that thrives through collaboration, creativity and interdisciplinarity."* SOTSEF. [2]

The Festival is managed by the Public Engagement with Research Unit (PERu) which exists to inspire and support high quality public engagement with research across all disciplines at the University of Southampton.[3] The event is run as part of British Science Week[4] and culminates in a day-long free event for families. Holography has featured in three ways in the festival over the last couple of years:

A. Holographic chocolate made with diffraction gratings was used in 2023 as demonstration by the research group of Dr Marcus Newton, Associate Professor in the Quantum, Light and Matter Group whose research focuses on the themes of nanostructuring, optical control and quantum coherence[5]. The chocolate was used to introduce audiences to concepts related to X-Rays, Lasers and Crystals. Chocolate embossed with diffraction grating was developed by *Morephotonix*[6], publicised by *New Scientist*[7] and the activity of making your own holographic chocolate was popularised by several scientists and engineers through social media from 2020 onward.[8,9]

B. A display hologram was used as a demonstration tool to introduce the theory of black holes and holography to audiences attending a lecture entitled: *Is Our Universe a Hologram?* By Dr Andy O'Bannon, Associate Professor of Theoretical Physics at the UoS in 2023[10]. O'Bannon held up an 8" x 10" Denisyuk display hologram (produced in the 1990s by the author) during his talk in a lecture theatre, with the hologram illuminated by the light from the data projector and tilted forwards to ensure a 45-degree replay angle of the hologram for the audience. O'Bannon described the optical hologram in relation to String Theory's concept of the holographic principle uniting Einstein's relativity with quantum physics.

C. A holographic artwork was used to engage the public with the Black Hole research of Professor Diego Altamirano[11] in 2022. During the day-long Festival the Holographic Artwork was presented to visitors through an impromptu audience intervention by Dr Sadie Jones, The UoS Physics and Astronomy School's Astronomy Public Engagement Leader and a Black Hole researcher. Jones spent ~2 hours talking to people about the research and the artwork. The hologram Black Hole (John 2022) art was located in a brightly lit 'Space Zone' opposite an art display by students inspired by Black hole research papers. The context for the holographic display can be seen below in Figure 1. The process of making and displaying the hologram – and its impact - is described below.

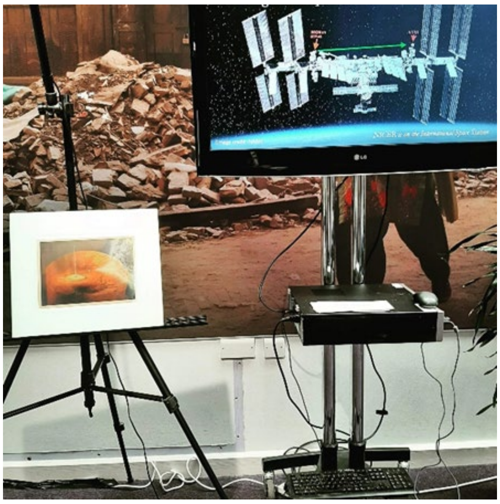


Figure 1. Holographic artwork at SOTSEF 2022. Photograph by the author.

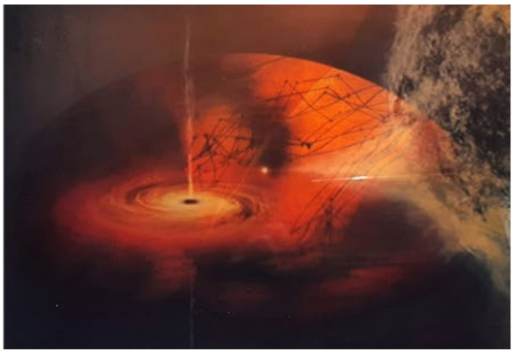
This section first covers a description of the artwork - including an explanation for using a technically flawed piece, and then describes those technical aspects employed.

3. THE ARTWORK

In 2022 the author received a grant from PERu at the UoS to produce a holographic artwork to engage audiences at SOTSEF with the Black Hole research of Professor Altamirano. Altamirano is an astrophysicist at the UoS with research interests in X-ray binaries, Black holes and Neutron Stars and is a skilled science communicator having run an international on-line black hole art competition entitled *Astroarteagujero*.[12] (Diego, 2021). While my role in the Physics and Astronomy department at the UoS is one of Science Communicator – I was able to interview Altamirano about his research interests, processes, and tools in preparation for producing the artwork – as an artist. As a practice-based researcher I am used to working with several distinct but complementary roles – such as artist and researcher. I was particularly interested to learn what element of his research he was most excited about – and produced a Powerpoint presentation quoting him and describing some of the simpler elements of his research – such as the telescopes he used to look at Black Holes – and how communicating to other astronomers what he had seen when he made a new discovery - fired him with enthusiasm. During our discussion I noticed that he was reluctant to show me his research data unless it was published – even though I could not have understood the intricacies of his research – or perhaps because of it. When astronomers communicate their research to the public, they use beautiful images of false-coloured stars to describe concepts – however in discussion with Altamirano it become evident that the visual language employed by the research was mathematical rather than pictorial. When I reviewed Altamirano's research papers – I became fascinated by one graph which used the term 'hard colour' – as if light or wavelengths could be solid – the concept seemed in direct contrast to the ethereal, transparent nature of holographic or spectral colour and chose to use that graph as an image in the artwork.

As a science communicator I wanted to be able to use the artwork to communicate a key concept to the audience: that black holes have a structure which can include jets. I incorporated a scientific illustration produced by NASA of the black hole Cygnus X-1[13] which Altamirano directed me to - into the artwork. The image involves a scientific illustration of the black hole which is approximately 15 times the mass of the Sun in orbit with a massive blue companion star. Astronomers used several telescopes including Chandra to study Cygnus X-1.

Figure 2. Black Hole (2022) 20.32cm x 25.4cm. Photograph by the author.

Figures 3. & 4. Black Hole details from different viewpoints (2022) 20.32cm x 25.4cm. detail, Photograph by the author.

The holographic artwork is a multi-media image including a transparent reflection hologram – a shadowgram - overlaying the illustration of a black hole. The holographic image is interleaved with the digital photograph - the transparent holographic image receding behind the digital photographic image. The image has an element of interactivity within it - with a subtle dynamism provided by the inclusion of fringes produced by the movement of the object during exposure. As an observer moves to-and-fro in front of the artwork the dark bands move. The absence of light within the hologram also references the darkness of the subject matter. The scientific data with the graph embedded below the surface of the hologram appears to have been ejected by the black hole along with a jet of matter.

There is a tension for artists when showing art holography to display holography audiences – a difference between artwork – and a hologram produced for display purposes. A display hologram tends to be bright, and flawless, however the late artist Anait challenged this presumption for holographic artworks in 1992 when in an exhibition at the Royal College of Art she presented a purposely dim hologram in the artwork *Water Lillies*. The murky appearance of the hologram reflected the content of the polluted water. Despite the imperfect nature of the artwork the pioneering artist Margaret Benyon said of it:

> *In my opinion her "Aurora" and "Water Lilies - after Monet, or Slow Death" are amongst the very best artwork made using holography.*[14]

While I am not comparing my own work to that of the heralded Anait, I am arguing for imperfection when relevant to the image. There were several technical issues with the hologram - which could cause a display holographer concern - that I kept in the final image for creative reasons: firstly, there was the movement – the image during the film exposure resulting in fringes - moving areas of darkness, and secondly, the edge of a collimating mirror I was using for the first time cut the image off in a semi-circle. I chose to keep the image in the hologram because it reminded me of looking through an optical telescope or a spaceship portal, drawing the viewer's attention to the artifice of the means of viewing the black hole despite the fact that we will never be able to get close enough to see a black hole as the image presented by the scientific illustration.

3.1 The Holography: Technique and Equipment

The hologram is a one-step shadowgram, produced with a 30mW Coherent Helium Neon laser and shot on vintage Agfa film. To produce the image an edited graph of Altamirano's was photocopied onto transparency (an acetate marketed as being non-birefringent) and mounted onto a ground glass screen to act as a mask. The Agfa film was pre-swollen for orange using a Triethanolamine bath, then exposed and developed with a pyrogallol and sodium carbonate solution. The developed hologram was bleached in an EDTA solution, dried, and then the pyrogallol and EDTA stain was removed with a potassium permanganate bath to leave a transparent film. The hologram was washed and soaked in a bath with acetic acid to prevent future printout. The process has been described fully in my PhD dissertation[15]. The image below shows the mask adapted from one of Altamirano's light curves.

Once finished and framed the hologram was displayed on a *Holixica* lighting rig – incorporating an aluminum tripod – and LED spotlight shown below in figures 1. above and 6. and 7. below.

Figure 5. The object is illuminated by laser light during the holographic process. Photograph by the author.

4. SCIENCE COMMUNICATION: WHY USE HOLOGRAPHIC ARTWORK?

During the festival Jones acted as an impromptu 'Explainer' (a term used to describe professional science communicators in science museums and centres) engaging visitors with the artwork – shown below in figures 6. and 7. In a 2014 study of children's visits to a science centre by the Sociologist Eric Jenson, Explainers were shown to increase audience understanding of scientific concepts by 7%.[16] I observed Jones at work, and the audience's reaction to the artwork and her explanations for a brief period during the event which - while informal - is an established method of artist evaluation during exhibitions as explained in artist Tine Bech's PhD 2014 dissertation:

> *Observations are used to find out what people do – how people physically interact with the artwork.*[17]

Jones spoke with approximately 200 people. I interviewed her a year later to determine her recollection of the event. I asked her whether it was beneficial to use artwork to engage the public with Black Hole research, she agreed and replied that there just aren't that many images available on Black holes – because research area relies on scientific illustration:

> *Yes! We don't really have many visual representations of black holes.*[18]

And in answer to why we should use holography Jones responded that holography was 'cool!' Her adjective implied that holography still has a positive status and had emotional impact on herself and our audience. So, the medium had an emotional impact which is helpful for longer term recall, but on reflection it should have been important to analyse communicated the science effectively.

5. AN ANALYSIS OF THE IMPACT

During my observation I noted several indications of in-depth engagement taking place. I saw 'pointing' by both Jones (shown in the figures 6. and 7. above) and members of the public, and I noted audience members talking and moving in front of the hologram with full attention paid to the work.

Many holographers will be familiar with having to clean audience fingerprints off exhibited holograms at the end of the day, and instinctively know that the prints are a positive indication that audiences have engaged with the spatial element of holography through poking at an image. However even pointing at a hologram is an indicator of engagement. In arts researcher Dimitra Christidou's 2012 PhD dissertation entitled: *Does "pointing at" in museum exhibitions make a point?* She Studies visitors' performances in three museums for the use of reference as a means of initiating and prompting meaning- making. she describes how pointing aids communication and highlights:

> *...the importance of using deixis, especially pointing gestures, for sharing content and context, directing and anchoring attention to an exhibit and for getting a conversation started in ways that language cannot alone do.* [19]

Figures 6. and 7. Dr Sadie Jones engages visitors with the holographic artwork and the Black hole research

Christadou argued that there are three main performative elements illustrating quality engagement: pointing; tagging; (or collecting others in the party to show them an exhibit), and physically moving to engage with an exhibit). When I asked Jones what she thought in-depth engagement looked like – she too gave the example of participants collecting family members to show them an exhibit – and repeating the explanation of what they had learned. The fact that the hologram encouraged movement by the visitors, and they were observed doing what Jones and I called the holography dance – moving to-and-fro and bobbing up and down in front of the hologram suggested quality engagement. Jones also said: dwell time, questioning, and exclamation were indicative of impact. With regard to dwell time, Arts researchers Silvia Casini in Communication and Evaluation in Science Museums in 2014, notes that art slows visitors progress through a science exhibit:

> *The artwork slowed down visitors' movement through the space...visitors (to science museums) are often distracted by too many stimuli and cannot focus...Art becomes a moment of pause and reflection in the context of the science exhibit, a moment to take a breath and look again.* [20]

So, artwork can be argued to pace audience movement through a festival.

5.1 In what way can using a holographic artwork hinder engagement with research?

One problematic aspect of using display holography for the purposes of Science Communication was the need to discuss what is, and is not, a hologram which arose multiple times during the festival. This is wasted time as far as engaging an audience in Black Hole research, detracting from discussing the research content. Dr Jones noted during our interview that she had to explain on more than one occasion that a contemporary theatrical production about the musicians 'ABBA' did not use holograms, but projected images[21]. It is frustrating to have to spend time on explaining 'fauxlography'(Fauxlography : not holography - a term introduced by Michael Page during a talk in ISDH2015 to describe Holography which was presented as such by the media but was in fact other forms of three-dimensional media) - the term then had a Facebook page dedicated to instances of it.[22]

However, it was not possible from discussion with Jones, or through my own observation, to ascertain what the visitors had learned about the research from the engagement. Formal methods for evaluating the impact of this activity as a tool for science communication – rather than as an artwork - were on reflection sorely lacking. It is common – even for professional Science Communicators not to do a robust job of measuring impact.[23] It is also difficult to both communicate the science and to evaluate its effectiveness. Planning for others to evaluate an activity you are delivering can be the best approach. (In my defence I had several management roles at SOTSEF which split my attention and the hologram was produced as an artwork, rather than a tool for science communication. It was only in retrospect that I realised that a more thorough evaluation could have been undertaken.) In fact, a plan for evaluation should have been produced as part of the grant writing application which was usually required by PERu. As a result of this analysis recommendations for future approaches are shown below.

5.2 Recommendations for future evaluation.

In line with the Arts Council's Generic Learning Outcomes (GLOs),[24] best practice in public engagement is to survey audiences for their enjoyment of the activity; any change in attitude or behaviour because of the activity; any indications that learning has occurred, and what audiences have learned. Having clear aims and objectives if an artwork is to be used as a vehicle for science communication would be beneficial. Evaluation approaches could include the following to determine benchmarks for success for others:

1. Objective to reach a minimum number of visitors: Evaluation method: determine accurate numbers of those who engaged with the artwork using digital clickers.
2. Objective to engage audiences of different ages, genders and experience of art galleries and science centres: Survey a sample of audience members - (perhaps using a competition as a potential motivator to complete an on-line or paper-based survey).
3. To note what percentage of audience members stop to view the artwork and what percentage pass straight by without engaging to determine whether particular demographics are more or less likely to engage with the artwork. Evaluation method: Observation and interview.
4. Objective: to encourage in-depth engagements with the artwork: Evaluation methods: determined by dwell time, gesturing, and engagement with explainer.
5. Evaluate average dwell time of audience members noting differences between age, gender and experience of visiting art galleries or science centres.
6. Survey audience members for their cognitive and affective responses to the artwork.
7. Survey audience members on their understanding of the content of the artwork.

These methods of evaluation may provide suitable aims and objectives for future projects – helping with grant applications when impact of engagement needs to be measured and summarised. While Silvia Casini, in 'Art in Science Centres' argues for the use of video-based multi-modal analysis of users' behaviour as a more appropriate method – observing and analysing what happens in front of an exhibit. She recommends video and conversational analysis.[25] However, this would prove problematic in a temporary festival situation in terms of resourcing (time and costs).

6. CONCLUSION

In conclusion, both holography demonstrations and holographic artworks can be useful for science communication at science festivals. Holographic artwork engages audiences emotionally and physically, deepening understanding of the subject because it makes audiences slow down. Having to move carefully to view an interactive artwork maintains audience member's attention in a busy environment. The audience can be seen to engage through pointing, tagging – or encouraging friends and family members to share their experience - and through questioning of an explainer to gain further information – all these aspects providing evidence of engagement. Science communication through art can make science more accessible, engage audiences in a more emotional and visceral way, and inspire collaboration between scientists and artists. Art can make science more human, more relatable, and more approachable for everyone. Art thus can play a vital role in improving the communication of complex scientific concepts. Having an explainer engage audiences with holography improves the information communicated. Having clear aims and objectives for the engagement – and a thorough plan to evaluate the impact of the engagement is highly recommended to aid further research. It would also be useful to determine the extent to which that deep engagement results in improved scientific knowledge. It is crucial to embrace art as a tool for more effective science communication at science festivals to maintain or boost the public's understanding of science and holography, with its inbuilt emotional impact, is placed perfectly to engage audiences with scientific research.

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The PERu Team, University of Southampton

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The ‘Real/Virtual’ exhibition of holograms at Gallery 286: Exploring the use of display holography in contemporary artistic expression

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ABSTRACT

Since its introduction in the 1960s, holography has attracted interest from scientists, engineers, physicists, and artists, resulting in a wide range of commercial, security, medical, and artistic applications. However, despite the emergence of a diverse international community of passionate holographers in the 1970s, this medium has not been well accepted in the contemporary art world. Paradoxically, recent technological advances have made holography more accessible than ever to artists: the materials required to make holograms, such as lasers and photopolymer film, have become much more affordable and portable.

Given the widespread application of virtual reality, and the increasingly ‘online’ nature of our lives and communities, I believe that holography offers an interesting perspective regarding the importance of embodied experience. Holography invites the beholder to exist simultaneously in the real world, where they can manipulate the motion, time, and visual qualities of the work, and in the virtual world created by the artist. The unique demands that holography places upon the viewer make it an ideal medium for contemporary artistic expression, with particular utility for exploring themes related to philosophy, technology, environmentalism, and history.

I was very pleased to accept the offer of Jonathan Ross to act as guest curator for an exhibition of holograms selected from his collection. The show, entitled “Real/Virtual: holograms from the 1970s to 2000s”, opened on April 4, 2023, at Gallery 286 in London, UK. In this paper, I will describe the featured works and discuss them from a contemporary art perspective.

Keywords: Holography, contemporary art, curatorial practice, Gallery 286, art theory

1. INTRODUCTION

Holography has been extremely successful its application to commerce, medicine, engineering, security, and anti-counterfeiting technologies. However, it has been less well accepted in the field of contemporary art, despite a long history of innovative artists using the medium to express sophisticated ideas, and the incredible aesthetic, conceptual, and phenomenological properties of the medium. This has resulted in many barriers for artists working with holography in terms of accessing funding, securing opportunities to have their work exhibited and collected in institutions, and in selling work. Given the importance of this issue for holographers, many researchers have speculated about the possible reasons for this exclusion[1]. Central to these conversations is the differences in the culture and standards regarding the presentation and discussion of new ideas in the different disciplines across which holography spans. For example, while new ideas in science are generally communicated using peer-reviewed articles that are accessed via searchable databases, new ideas in art are often presented via art exhibitions, which are documented, shared, and discussed via art reviews and critiques. Greater understanding of these distinctions could help holographers to carefully choose the context in which to present their work, according to the type of dialogue they would like to elicit. Indeed, several prominent holographers have examined the factors associated with successful installation of holograms in gallery settings,[2,3] as well as new methods of critique[4]. Such efforts are important in reducing confusion regarding the interpretation of holograms created to explore scientific or technological ideas, in contrast with those that are in dialogue with contemporary art history, thus creating greater visibility for contemporary artists working with holography.

Here, I describe an exhibition of 15 holograms from the Jonathan Ross collection, which I was invited to select as guest curator in 2022. When creating the exhibition, I looked through the entire catalogued collection, and considered the ways in which holography has been excluded from contemporary art discourse. I attempted to choose works that were united by specific aesthetic and conceptual themes, and that strongly relied on the medium (holography) to communicate the meaning of the work. I hoped that viewers unfamiliar with holography history would to be able to engage with the exhibition, and that my curatorial decisions would facilitate the positioning of the works within the history of contemporary art.

Much of contemporary art discourse relies on the documentation of artworks that have been installed in a curated show in an art gallery. The step of installation in a gallery enables the work to be presented in specific conditions for viewing, and signals the approval of the gallery and curator, which functions similarly to publication in an academic journal following successful navigation of the peer-review system. The gallery setting, which is a specific context determined by the artist and curator together, is important for contextualizing each artwork in relation to the others in an exhibition. Curating an exhibition involves selecting artworks according to specific conceptual themes, historical references, phenomenological qualities, and other artistic properties. A strong curatorial vision can guide viewers to attend to specific qualities of the works, enabling greater understanding of their meaning, significance, and importance in art history. Stronger adherence to curatorial practices informed by art theory when exhibiting holograms could increase the visibility within contemporary art criticism of holographic works and artists.

To help explain my curatorial choices when assembling the exhibition, I will provide some context about the experiences that have shaped my perspective. Given the closure of many institutions for holography globally, as well as the corresponding decline in exhibitions of holography in recent years, many people have never seen a fine art hologram in real life, and many more are unaware of the existence of holography as a medium. This was my case, even as I completed a Master's in Fine Arts (MFA) in Interdisciplinary Contemporary Art at Simon Fraser University in Vancouver, Canada, in 2013, with a thesis exhibition comprising a series of sculptures using multispectral paints and resins. I was deeply inspired by the work of West Coast artist Jerry Pethick, who used multispectral foils in his collage and sculptures, and was involved in the creation of the School of Holography in San Francisco. However, throughout my graduate studies I did not encounter information that indicated that it was possible for artists to work hands-on with holography, and so I never considered this medium as something I could use to make art. I was lucky enough to have a chance encounter with holographer Melissa Crenshaw in 2021, who is a good friend of my aunt, where I learned about the existence of the international holography community. Having never seen an art hologram in real life, I enrolled in Linda Law's online course "Understanding Holograms" and contacted Jonathan Ross, who was involved in the creation of holograms starting in the mid 1980's, and has built one of the largest collections of holograms in the world.

Before I studied contemporary art, I had minimal experience with academic art theory. I had been a researcher in the fields of neuroscience and electrophysiology, studying time perception and rhythm synchronization, and felt unsatisfied with the behaviourist perspective as an explanation for art and creative behaviour. I considered adopting a neuroaesthetic perspective, but found this to be ineffective when analyzing artworks that had conceptual content. Ultimately, I decided to study art at a contemporary art institution. Given my science background, I had to learn a new vocabulary, history, aesthetics, and practice, as well as a new peer review system – art reviews and critiques. After two challenging and exciting years, I emerged with a completely new understanding about what art is, and a perspective that I feel has deeply enriched my ability to engage with history and culture. I feel grateful to be able to enter the conversation about holography with a perspective that I feel is shared by many holographers – an ability to approach ideas from both a scientific and an artistic perspective.

When engaging with the works in the collection of Jonathan Ross, I was struck by the wide range of holographic applications, from portraiture to highly realistic three-dimensional representations of objects, to the construction of new environments and relationships between features that could only exist in holographic space. I made a list of works that seemed to explore themes that I felt would resonate with viewers familiar with current ideas in contemporary art, such as world-building, self expression, feminism, history, and psychology. As we looked through the collection, Jonathan Ross provided the history of each of the works, and we discussed the ways in which they might have been perceived in the time of their creation, and speculated about how people would receive them in the current moment.

Holography has unique qualities that make it particularly relevant to contemporary artistic expression. When interacting with a hologram, the viewer is challenged to exist in both the real world and a virtual world simultaneously. To explore the virtual world created by the artist, it is necessary to move in real space to manipulate the motion, time, and visual qualities of the hologram. This duality of experience offers an important metaphor for the way in which modern humans are required to live both online, in a digital world of our own construction, and in the real world, by nature of our physical bodies. Interacting with holographic works of art may enable us to obtain insight regarding challenges specific to maintaining a real/virtual balance in the modern age. For instance, our relationships with our bodies, one another, and the environment require that we tend to our physical and emotional needs in the real world, while we face increasing pressure to maintain a presence in the online world to find employment, community, and to exchange intellectual and creative ideas.

Given the lack of visibility of holography in the art world, I feel certain that there are many artists, curators, and collectors who are unaware of the potential and incredible history of this medium. Accordingly, I selected holograms from the Jonathan Ross collection that I think demonstrate a range of ways in which the medium can be used to offer new artistic perspectives, create new spaces, and consider our own psychology and history. I chose the following works in which the artists created new virtual spaces to be explored by the viewer: 'Crystal Beginnings' (1977) by Steve Benton, 'I'm Spinning Around' (2005) by Amy Rush, Iñaki Beguiristain's 'Reflections' (2002), Dan Schweitzer's 'The Seed' (1980), Rudie Berkhout's 'Breakthrough' (1990), and Paula Dawson 'Water Ray' (Study for Luminous Presence) (2007). New geometric planes, impossible and real at the same time, are featured in Caroline Palmer's 'Diamonds and Stripes' (1989) and Jacques Desbiens' 'Distortions' (2009). I included works that explore changes in human activity or perceptions over time, such as Patrick Boyd's 'Jackson Makes it to Manhattan' (1990), Dora Tass's 'Perturbing Objects' (2015), and Harriet Casdin-Silver's 'Venus of Willendorf (1991),' the last of which which has strong relevance to today's conversations about body positivity and fat phobia. Given my interest in neuroscience, I was very intrigued by the use of holography to explore human cognition in Susan Cowles 'The House of Moons' (A stage for the Chymical Theatre') (1988) and Ikuo Nakamura's 'Memory II' (1999), as well as the psychological experiments with colour and abstraction in portraiture employed by Steve Weinstock in 'Big Lucian' (1992) and Ana Maria Nicholson in 'Collaborative Work 3' (1989), which was made in collaboration with Rudie Berkhout. The exhibition, entitled "Real/Virtual: holograms from the 1970s to 2000s", opened on April 4, 2023, at Gallery 286 in London, UK, and ran until June 21.

In the following section, I will provide some background about each work taken from the exhibition catalogue, and discuss my interpretations of the work.

2. ARTWORKS

2.1 Steve Weinstock - 'Big Lucian' (1992)

"Big Lucian" is a mirror-backed white light transmission hologram on glass, featuring an abstract face with extremely vivid colours. The mirror has been removed around the face so that the wall behind the piece can be seen through the glass, and the work is surrounded by an ornate brown frame. When moving around the piece, the eyes of the figure, which are cut out and appear a different colour from the rest of the face, shift with a spiral interference pattern that approximates the gaze of the figure. The colours include many shades that are uncommon in light-based art, such as magenta, salmon pink, and copper, and they shift as the viewer moves around the work. The vivid colour is apparent from a wide viewing angle.

The intense colour in this work is contrasted with the stark caricature of the face, with its intimidating spiral eyes. The hologram has a shallow depth, only about 0.5 inches, which adds to the visual ambiguity of the work – it is not immediately apparent that the piece is a hologram. The face appears to be floating in space, and with its abstracted features and intense luminosity, is highly salient. Given the vast neuronal resources allocated to facial expression, facial manipulation can be perceived as disorienting and psychedelic, which is the case with this work. This piece shows how holography can be used to increase the complexity of a portrait, as well as to create shifting features that bring into question the stability of identity. The uses of perceptual ambiguity, abstraction, and shifting colour create a unique phenomenological experience for the viewer, and illuminate the possibilities for abstract holographic portraiture.

Figure 1. Steve Weinstock (b. 1965) ‘Big Lucian’ 1992, mirror backed white light transmission hologram (12.5 x 10”) (Photo by Jonathan Ross)

From the exhibition catalogue[5]:

American artist Steve Weinstock has focused on holographic colour mixing and the creation of rainbow shadowgrams. This piece, made while he was living in Prague (although shot in his studio in L.A.) was initially exhibited in a show called ‘Faces+Places’.

“Places came from all the photography I was doing of the places I’d see every day in Prague. Faces came from the fact that I’d always been doodling and painting faces throughout my life. I was a big fan of Lucian Freud’s work at the time and I think I discovered the picture that I used in a newspaper or magazine article. As far as I can recall it was a current photo of him and I was just struck by how intense the gaze was – more so than in his self-portraits.

I guess I was sort of hoping to do a holographic color mixing as an interpretation of his painterly color mixing in his portraits. The thing that made the hologram really special though was the spiral interference patterns that occurred right where his eyes should be (there’s one on the nose also but I conveniently disregard that one). It gave the face a life and makes it feel as if he’s looking right at you viewing the hologram. The hologram itself was probably a 4-exposure rainbow shadow gram - 2 exposures in each masked area.”

2.2 Ikuo Nakamura - ‘Memory II’ (1999)

“Memory II” is a white light transmission holographic stereogram on glass, positioned vertically on a wooden block and presented on a plinth at eye-level. The central figure in the piece is the bust of a young girl with blue eyes, looking out at the viewer. She is surrounded by rectangular images of important historical events, all of which appear to relate to historical tragedies or war, and appear to be floating in space around her head with different orientations and distances between them.

This piece uses holography to represent human cognition, specifically, memory, on not just a personal scale but also a societal scale. The historical images, with their strong emotional valences, can only by fully explored by moving around the hologram. That they have different orientations and shifting positions in space, while always anchored to the central figure of the girl, could function as a metaphor for the permanence of tragic events in human history as part of our public memory, or collective consciousness. This work is important in the history of holography in terms of its use of multiple images to represent different moments in time, and thus the spaces and connections between different histories.

Figure 2. Ikuo Nakamura (b. 1945) 'Memory II' 1999, white light transmission holographic stereogram (digital image output) (19 x 23 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

Ikuo Nakamura is a holographic artist and filmmaker based in New York City. He studied Physics at Tokyo University of Science and Holography at New York Holographic Laboratories in 1984. Initially, Nakamura focused on mastering the wealth of colours in white light transmission holograms, but his interest soon crossed over with other electronic and interactive technologies. This led him to create new holographic hybrids such as Rainbow Dance I (1990) and Neuro Hologram (1993-96), which serve as interfaces between the viewer's brainwave and the hologram, and illustrate the Brain as Hologram theory.

Nakamura's interest then shifted back to seminal/master laser transmission holograms for in situ installations. Some of his notable works include the life-sized "Fossils" site-specific laser installation and "Thera" with video projection. His work has been exhibited and awarded worldwide, and he also served as co-director of the Center for Holographic Arts in New York.

In 2013 Nakamura's 3D film 'Atmosphere', a documentation of the northern lights, won numerous awards including the Paul Wing Award and The Best 3D Film of the Show at the National Stereoscopic Association Convention, and a Special Audience Award for 3D at BEFILM Festival in New York.

Of his work, Memory II (1999), Nakamura states:

"We are constantly surrounded by a multitude of images on TV screens, in printed media, and on the Internet. Unfortunately, many of these images are violent and not only impact personal memory, but also public memory. I have compiled a selection of shocking TV footage from different regions and historical periods, centered around a young French girl named Nicole. This piece aims to illustrate the state of humanity and the exponential increase of shared memory through the accumulation of such images."

2.3 Ana Maria Nicholson - 'Collaborative Work 3' (1989)

"Collaborative Work 3" is a pulse laser hologram that features long curved fragments of images of the faces of the two artists, shown in deep purple, pink, and blue shades. As the viewer moves in space, the images of the artists overlap, so that they appear to be occupying the same position. The emotional valence of the facial expressions is ambiguous, and the artists are depicted with their eyes closed.

This piece is one of a series in which the artists used pulse laser holography to create abstracted portraiture, which was layered and assembled into a composition. Berkhout and Nicholson depict the creative combination of their identities through this process, enabling fragments of each artist to exist in the same position in space. This work communicates the potential of holography for exploring the connections between people, the possibilities of multiple identities, and lived experiences connected to the same space in time and history, and shows how these elements can be combined to create new aesthetic forms.

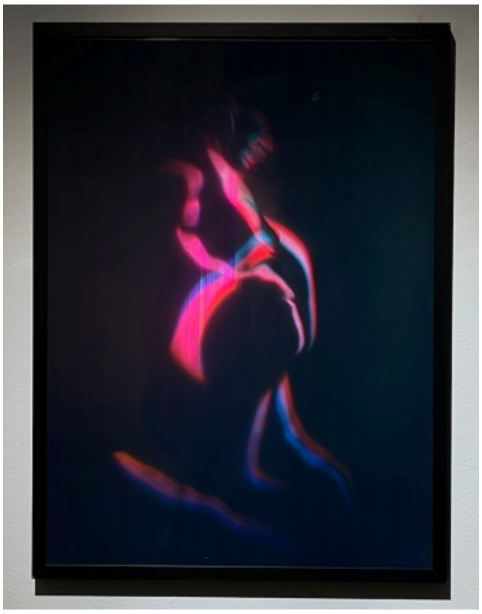

Figure 3. Ana Maria Nicholson (b. 1939) – 'Collaborative Work 3' 1989, pulse laser reflection hologram on glass, made in collaboration with Rudie Berkhout (43 x 32 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

Ana Maria Nicholson and Rudie Berkhout are both prolific holographic artists who each shaped different genres of the art form.

Nicholson primarily works with portraiture, having created holograms of celebrities, spiritual leaders and diverse people. Her series 'Into the Night' captures the plight and power of women. Created in single and multiple pulse laser exposures, the women hold a space. Berkhout crafted holograms with laser light, creating spatially animated landscapes from simple objects and optics. His work stood out in the field of holography, exploring the concept of holo-kinetics through optical spatial dynamics.

Nicholson and Berkhout first met at the Museum of Holography where Nicholson was the director of the Portrait Studio. She writes that
"At that time I had begun to feel a dissatisfaction with the constraints of a holographic portrait. They were, on the whole monochromatic, their depth limited, the space ungenerous. I speak here of reflection holograms. I had gone to see an exhibition of Francis Bacon's portraits and I was overwhelmed by them. Those liquefying faces, tormented by the weight

of the flesh haunted me. Rudie and I began our conversations on how best to break the mold. How to have portraits be more abstract, more pliable, perhaps more universal. To break up the face, we cut out different shapes out of pieces of cardboard and removed the diffusing screen from the object beam. This created a small, tight light source so that only the parts of the face that were uncovered were illuminated. That is why, for safety, our eyes are closed in all the holograms. Those were the masters, each with a different shape, different size, some recognizable as features some just abstract shapes. I took the masters to our lab in Long Island City and sometimes combined two or more masters, doing a lot of color combinations with triethanolamine."

2.4 Patrick Boyd - 'Jackson Makes it to Manhattan' (1990)

'Jackson Makes it to Manhattan' is an achromate reflection hologram on glass, superimposed on a black and white photograph in a wooden frame. The photograph features a pit bull on the sidewalk in front of Katz's Delicatessen, which is a historic kosher-style delicatessen in New York City. As the viewer changes position from side to side, a green hologram flashes into the space over the photo. The hologram shows the view from the outer deck of a ferry heading towards Manhattan, with people looking towards the tall buildings of the city. Although the piece was originally made as an achromate hologram, which would have been seen as a luminescent silver, the colours have changed over time such that the hologram is now a bright green.

In this work, Boyd incorporates encourages us to think about the layers of history contained in an iconic place: New York City. The hand made aesthetic of the wooden frame, along with the candid style of the photograph, signals a personal journey, memorialized in an intimate way. Contrasted with the photo and dark wood, the bright green hologram is ghostly and surreal, and appears as if it is a memory that has suddenly entered the viewer's mind. The change over time in the hologram from silver to green could enhance the degree to which the work is read as a hologram, and, in conjunction with the symbolic features of the work, anchor it to the urban art aesthetic of NYC at the end of the 1980's and beginning of the 1990's. By including an image of a pit bull in front of an iconic NYC deli, Boyd has chosen symbols that represent the romanticization of urban culture in NYC during the time the work was created. However, by superimposing a hologram showing the view from the Staten island ferry approaching Manhattan, Boyd references a different type of anticipation regarding NYC: the promise of a new world for the many immigrants who arrived in North America via nearby Elis island. This work is a potent demonstration of how a place can hold multiple meanings simultaneously, and invites us to connect with history by imagining the shifting contexts of iconic landscapes.

Figure 4. Patrick Boyd (b. 1960) – 'Jackson Makes it to Manhattan' 1990, achromate reflection hologram and photograph in box frame (8 x 10") (Photo by Jonathan Ross)

From the exhibition catalogue:

In 1989-90 Patrick Boyd was awarded an Artist in Residence at the Museum of Holography in New York. He decided that he would attempt to use holography as a documentary medium, recording events and scenes that he found in everyday life.

In a 1994 statement he explains that "Holography and photography had been my chosen media for some years, and at this time I started to experiment with combining the two to make holographic stereograms (holograms generated using a series of photographic images). To me there is nothing as visually fascinating as a stereogram, with which one can incorporate the element of time into a work. My holograms use a chronological sequence of 36 exposures, shot in quick succession which in the finished stereogram give the effect of time passing as the viewer moves his eyes from left to right. The work is essentially an interactive experience for the viewer, but during which he remains in control, deciding for himself the speed with which the image is revealed and explored, frame by frame. Using only 36 exposures does mean that the image is slightly jumpy and loosely restricts me to landscape as opposed to portraiture, but the pixelation effect gives a 'handmade' look to the work which I really like. Otherwise it could be too uniform and sterile."

"When I first arrived in New York I stayed on Staten Island, where getting to the city every day involved a spectacular boat trip with one of the most impressive views in the world.

That trip is absolutely synonymous with most people' s idea of arriving in America, as it is very close to Ellis Island, once the main immigration port of the U.S. Of course, after about two weeks the magic had completely worn off..."

2.5 Dora Tass - 'Perturbing Objects' (2015)

'Perturbing Objects' is a dichromate gelatin reflection hologram on thick glass with no frame. The image features a typewriter, which is distorted and distant looking, and is made using pseuocolour holography, which creates a rainbow effect with colours that are simultaneously rich and muted.

Tass uses pseuocolour holography to represent the typewriter as a timeless imprint of a tool for human communication. The ghostly colours and blurring of the image elevate the typewriter as a symbol of the human drive to document and communicate information about our lives to other humans in different epochs of history. This piece shows us how the medium of holography can be used to blur and to create distance, as well as to insert the impression of vast amounts of time between the viewer and the portrayed features of the work.

Figure 5. Dora Tass - 'Perturbing Objects' 2015, dichromate gelatin reflection hologram (41 x 34 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

Perturbing Objects is from the 'Archaeology of the Future' series of light sculptures made by Dora Tass in collaboration with August Muth's Light Foundry studio in Santa Fe, New Mexico, currently a world centre of excellence in the production of large format dichromate gelatin holograms on archivally stable laminated glass plates.

Surrealism and Dada inspire these artworks, suspended between past and future, familiar and unfamiliar, tangible yet intangible.

In this series, elements such as typewriters, cameras, lenses, newspapers, ancient stones and words are the subject matter which serve to preserve culture as a medium of communication, history and identity. These vintage objects are removed from the oblivion of time, dematerialised in surreal light sculptures, in transition from the age of 'Enlightenment' to the contemporary age of 'Photon'. (Text adapted from one on doratass.com)

2.6 Caroline Palmer - 'Diamonds and Stripes' (1989)

'Diamonds and Stripes' is a multi-colour reflection hologram on glass, presented with a wooden block on the back so that the hologram is slightly protruding from the wall. The work features an intricately patterned geometric plane, with symmetrically organized colours and lines that change with the viewing angle. The piece was originally made to appear black, yellow, and orange, and over time has shifted to green and blue.

This work explores the fundamental effects of colour and pattern. The depth of the hologram is not easy to discern, and so the work does not necessarily invite the viewer to enter, but emphasizes the relational properties of geometric forms. The shifting of the complex pattern creates a shimmering effect as the viewer moves around the piece, eliciting feelings of mystery and excitement. The work seems to explore universal truths about light, pattern, and colour, beyond concrete ideas of space and time. The work brings to mind the many geometric themes that have been employed in religious artworks, such as stained glass windows in churches and tiled mosaics in mosques. This piece uses holography to elevate the fundamental nature of colour, light, and geometry to a spiritual level via careful control of the physical properties of the components. It is evident that the elements of the work are very carefully considered, with the goal of inducing the maximal phenomenological effect in the viewer. This work emphasizes the potential of holography for manipulating perceptual experience in a way that is purely tied to the recognition of form and shape, which is a fundamental element of visual processing.

Figure 6. Caroline Palmer (b. 1957) - 'Diamonds and Stripes' 1989, multi-colour reflection hologram (10 x 8") (Photo by Jonathan Ross)

From the exhibition catalogue:

"I first became involved with holography in I984 and was interested particularly in the application of holography in museums. I set up a holographic studio trading as 3DI and produced an 'Ancient Art Series'.

From 1987-1989 I was a student at the Royal College of Art, during this time my direction changed and I became more interested in the kinetic and optical qualities of holograms than their 3-dimensionality. My work was concerned with geometric pattern and the holograms were experiments in spectral colour mixing in space (i.e. off the picture plane).

Through my practical experience of working with light I became more interested in its metaphysical aspect and went on to research a Ph.D thesis on 'Light in Sacred Art' at the Prince of Wales's Institute of Architecture."

From the website of the Jonathan Ross collection:

"These two holograms [Elevator 1989 and Diamonds and Stripes 1989] are part of a series which I made of lines of light. They were intended to illustrate one of the most fundamental qualities about the nature of light, namely that it moves in straight lines according to geometric laws. I was also keen to show how spectral colour could mix in space and was not dependent upon the surface of the picture plane. Holography provided a unique medium in which to explore the dynamic quality of light and colour."

2.7 Harriet Casdin-Silver - 'Venus of Willendorf 1991' (1991)

'Venus of Willendorf 1991' is a nickel shim stereogram showing a nude woman standing at an angle, with a confident posture. She blinks and moves slightly as the viewing angle changes. The woman is shown 4.5 inches tall, and her figure references the statue of the same name and size discovered in Willendorf, Austria. This sculpture, which is estimated to have been made in 25,000 BCE, is considered to be a prehistoric fertility figure, and is one of the first examples of human representational art.

This work, which is potentially one of the most famous art holograms (featured on the cover of Sculpture Magazine), is an excellent example of how holography can be fundamental to the meaning of a work of art. Here, the image of model Christiane Jung is elevated to a god-like status via her portrayal as a shimmering hologram, standing nude, confident, lifelike (with natural movement), and timeless, in reference to the ancient deity figurine. The choice to create the hologram so that the figure is the same size as the ancient sculpture emphasizes the similarities between the two bodies, and encourages viewers to imagine how ancient humans felt when worshipping similar fertility symbols. Holograms of objects often appear to have a timeless quality, likely because the viewer can control the position of the work in time according to their own movements. Thus, holography can be used to explore ideas about change over time, historical events, and universal truths. This work illustrates how beauty standards have changed dramatically throughout our history, and invites us to consider different ways of thinking about female bodies in the present moment. This piece is refreshing in its representation of the female body from a feminist and queer perspective, and is clearly in dialogue with other works created by holographers during this period.

Figure 7. Harriet Casdin-Silver (1925–2008) - 'Venus of Willendorf 1991' 1991, nickel shim stereogram (180 x 98 mm) (Photo by Jonathan Ross)

From the exhibition catalogue:

Casdin-Silver was an American sculptor and pioneering holographic artist who created work in some of the leading facilities worldwide from London to Leningrad and was a Senior Fellow at the Center for Advanced Visual Studies at MIT. Her still life works often exploit the pseudoscopic potential of holography to turn objects inside out and flip them beyond the picture plane, while her nude studies unflinchingly confront age and imperfection.

Venus of Willendorf 1991 was created as a cover image for Sculpture Magazine with the collaboration of Hologram Industries in France, using the stereogram process which records a film sequence of the subject with a camera moving along a track, subsequently converted to a holo-cine hybrid by projection through a laser/ optical printer. The image was mass-produced on hotstamping foil and a limited edition created from the nickel shims used in the printing process. An achromate technique was employed to give the work a cooler sculptural feel than would have resulted from a typical embossed rainbow hologram.

The concept was to create a contemporary response to the prehistoric fertility figure discovered in 1908 and estimated to date from circa 25,000 BC.

Having been told that "There are no fat people in Paris", Casdin-Silver unearthed "L'Association pour la Défense et l'Épanouissement des Personnes Fortifs", (Association for the Defence and Acceptance of Fat People), whose mission was to promote a positive image of plus-size women and who provided Christiane Jung, a perfect model for the project.

The original Venus of Willendorf sculpture in the Naturhistorisches Museum in Vienna is approximately 4.5 inches high and the holographic version is similarly small and lacking in feet. CasdinSilver remarked that she "liked the swell of the body across the holographic surface, and the confidence and strength of this woman as she emerges from the surface plane".

2.8 Susan Cowles - 'The House of Moons (A stage for the Chymical Theatre)' (1988)

'The House of Moons (A stage for the Chymical Theatre)' is a reflection hologram with two plates, placed side-by-side on a large piece of paper with an ink drawing. The holograms are framed with black-painted wood, and the whole work is mounted on wood with a thin black frame. The holograms are dark green, and appear to portray a multi-faceted space, which shimmers as the viewer moves in relation to the piece. The space contains vertical strips of patterned surfaces featuring moon shapes, and similar shapes are positioned on the surface of the work, emphasizing the impression of depth. The ink drawing positions the holograms as if they were on a stage, with thick, swooping lines denoting the edge of the stage and ceiling.

This work creates a remarkable juxtaposition between the highly technical holographic plates and the simple technique of ink on paper. That this piece is about human cognition, and particularly, the feeling of being in the world, as in having one's cognitive processes on display, is clearly communicated while retaining an elegant subtlety. Cowles emphasizes vulnerability in her choice of ink on paper, as well as in the complex hand-made patterns within the holograms, to show that the work is exploring a sensation that is personal, while using holography to portray the human mind as a mysterious, glittering space. With this piece, Susan Cowles simultaneously asks us to consider the challenges and magnificence of the human experience.

Figure 8. Susan Cowles (b. 1962) - 'The House of Moons' (A stage for the Chymical Theatre') 1988, reflection hologram (2 plates, 40 x 30 cm each, on paper with ink) (Photo by Jonathan Ross)

From the exhibition catalogue:

Susan Cowles studied holography at the Royal College of Art between 1984-86. Her artwork combines drawing, painting and sculpture with the technology of holography. Her stated objective is to use archetypal themes and symbols which explore the self and its position within the structure of humanity.

Holograms from this period of her career are in the collection of the V&A Museum, London.

She moved to New York in the late 1980s and lives and works there to this day.

Back in 1994 she wrote of this work, "The House of Moons is a 'stage'. The meaning of the word 'stage' in this instance is multifaceted. It is a "physical stage", a place where a performance of a divine nature may occur, it is a "stage of artistic development", it is a "stage of Life". The hologram (poetically speaking) is intended to contain all the elements of a perfect dance, i.e. it represents the hidden information that human consciousness applies to move with grace and create a perfect coordinated work of art in space and real time. This piece is very personal, it is a map, a map of the interior mind which shows visual clues as to the past, present and future. All images stem from it and all images will go back to whence they came.

"Visually the hologram has multi-layered images of phases of the moon which are set on a circular spatial arrangement within the holographic space. On the bottom of both panels a small mirror was placed and if the viewer looks carefully the holographic space extends downwards and forms a vertical axis dimension inside the hologram. As the viewer moves around the piece a band of rainbow colour (diffraction grating) lights up the surface. This prompts the viewer to study the surface closer and notice the mark making within the hologram. I intended to create a cathedral-like effect within the space so the viewer would experience a sense of reverence, of being transported to another place and space which extends all boundaries of common logic. It is an image which must be imprinted in the mind, like a memory image, then its talismanic properties will take effect and forever transmute in the thoughts of all who lay their eyes on it."

2.9 Rudie Berkhout - 'Breakthrough' (1990)

'Breakthrough' is a white light transmission hologram on glass in a silver frame, suspended from the ceiling and illuminated from behind. It is features two abstract shapes, created using multiple exposures, which project out from the viewing plane as well as backwards, creating the impression of expansive depth and space. The shapes are different colours, and shift in both position and hue as the viewer moves with respect to the work.

Rudie Berkhout became a well-known holographer as a result of his works that explore interactive holographic space with remarkable colour, depth, and the use of multiple shifting components. His holograms are environments to be entered and explored, necessitating a great amount of movement in real space, with vivid colours that shift according to the viewing angle, components with exceptional depth, form, and texture, and precise viewing angles that obscure certain elements so that the entire piece cannot be viewed all at once. This piece is very important in the progression of his visual style, and the name is appropriate for both the position in his artistic trajectory and the sensory experience of the work. It marks the first time that he combined abstraction and figurative imagery to create this new type of virtual world, which he would continue to explore throughout his career.

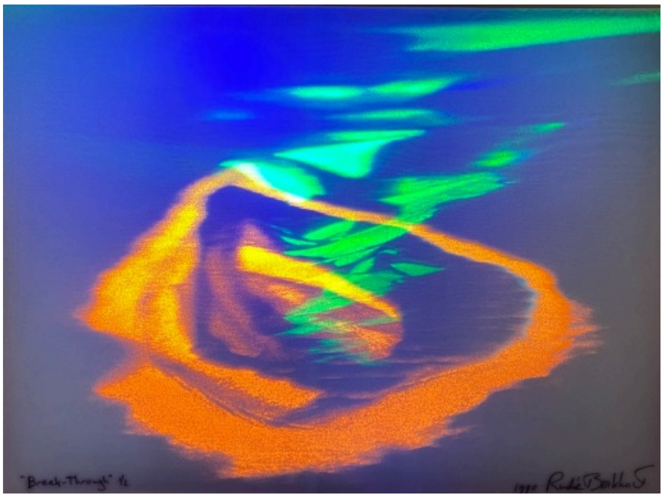

Figure 9. Rudie Berkhout (1946–2008) - 'Breakthrough' 1990, white light transmission hologram (30 x 40 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

Rudie Berkhout was born in Amsterdam and first encountered holography when he moved to New York in 1975.

He was immediately drawn to this new imaging process, finding in holography the "possibility of working with advanced technology outside a corporate structure and exploring it as an art medium".

Berkhout took a few courses in holography and worked with some of the studios emerging in New York at the time but soon decided to establish his own laboratory and developed a recognisable style of abstract and geometric imagery, using the white light transmission technique and the DIY 'sandbox' isolation table developed by West Coast holographers, which combined to make holography accessible to independent artists.

White light transmission holograms are created by sacrificing the vertical parallax of a laser illuminated transmission master and in the process acquiring a rainbow colouration which changes through the spectrum as the viewer shifts position vertically. By the use of multiple masters a holographic artist can overlay these rainbow images and create a multi coloured three-dimensional composition.

In the 1980s Berkhout began to use the sand that is used to stabilise his optical components as an element in his compositions. He found that "the grains of sand complement the graininess of the laser speckle and the immediate hands-on modelling possibilities of the sand are wonderfully low-tech in contrast with the high-tech methods of the recording process." He used sand "to create a feeling of expansiveness while suggesting brushstrokes floating in mid-air, with no connection to a surface. I like the work to oscillate between landscape and abstract painting, challenging viewers and jolting their usual perception of the world".

'Breakthrough' was exhibited by Berkhout in the New Directions in Holography exhibition at the Whitney Museum of American Art in 1991, that prestigious gallery's first showing of exclusively holographic work, alongside British holographers Wenyon and Gamble.

2.10 Dan Schweitzer - 'The Seed' (1980)

'The Seed' is a white light transmission hologram on glass, which is presented vertically on a wooden block on a plinth and lit from behind. The work was made by transferring six master holograms to the final white light piece, and according to the artist, if the viewer looks closely, it is possible to see a number of different features including Einstein's face, representations of photons, and a slowly rotating earth. The work has extremely vibrant colours, particularly shades of red, orange, blue, and green, and the shapes appear to spiral through the viewing plane as the observer moves from side to side.

This piece contains a remarkable world of shifting colours, shapes, and textures that appear to emerge out of empty space, projecting in front of the piece of unframed clear glass. Dan Schweitzer's work inspired many artists and collectors by demonstrating the phenomenological potential of holography: the work is attention grabbing and invites the viewer to move around to try to identify the hidden figurative components within the work. The way in which the microcosm of the artwork suddenly manifests and appears to hover in space acts as a metaphor for the invisible forces of physics at play all around us in the natural world, something which physicists such as Einstein sought to visualize and describe.

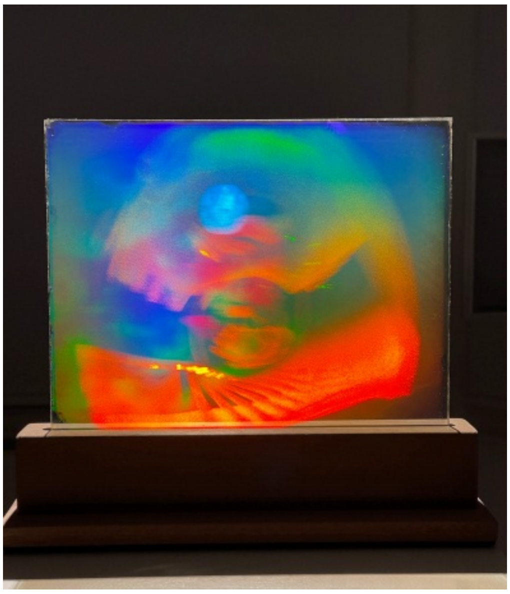

Figure 10. Dan Schweitzer (1946–2001) - 'The Seed' 1980, white light transmission hologram (8 x 10") (Photo by Jonathan Ross)

From the exhibition catalogue:

I [J. Ross] first saw 'The Seed' on a visit to New York Holographic Laboratory in 1982 and had never had a visual experience like it before.

I eventually bought his personal Artist's Proof from Dan's widow after his untimely death in 2001. This is the first time it has been exhibited in the UK. His earlier work "Movie Theatre", in which an integral hologram shows a self-portrait of Dan reaching out from a movie screen to grab a figure from the sculpted audience, was the deciding factor for my involvement with holography, when I first saw it in 1978. It literally grabbed my attention and convinced me that this was a medium that I wanted to engage with. J.R.

Following an early career in theatre, Dan Schweitzer learned holography at the New York School of Holography and worked as an instructor there before establishing New York Holographic Laboratories in the late 1970s with his colleague Sam Moree. He was one of the founders of the Holo Center in New York with Ana Maria Nicholson.

In a presentation at the Art in Holography -2 conference in Nottingham, Schweitzer stated that "My fascination for holography stems from my attraction to the light and the ability to 'sculpt' this energy. Light, it seems to me, is the most effective medium to use when attempting to visualize an idea. Ideas themselves seem to be composed of light….As time is often a theme (in my work) many of the images involve the use of special effects devices to create some kinetic event." He explained that these devices could be as simple as a circular hole cut in cardboard which employs the concept of 'hyper parallax' to create the illusion of a rotating globe. Another device which he called his "Time Machine" was a curved mirror with a dent in it. "With careful selection and recording, mundane objects are elevated to the sublime", for example in 'The Seed', "…a kitchen dish drainer becomes music or perhaps an ominous mushroom cloud." Schweitzer's work frequently incorporated elements sculpted by him, representing protagonists in a dramatic narrative. For example in 'Thendara', another work in the collection, a solitary figure (Dan's alter ego) sits at a table bathed in the rainbow of light pouring through a window, perhaps waiting for inspiration. In 'The Seed' you have to look closely to see that "Einstein's convoluted face is revealed studying the flying photons before him as the earth rolls slowly by. It involved six master holograms transferred to the final white light work."

2.11 Steve Benton - ‘Crystal Beginnings’ (1977)

‘Crystal Beginnings’ is a white light transmission hologram on glass, suspended from the ceiling and lit from behind. The work shows a matrix of points of rainbow coloured light, with the points starting near the image plane, and then gradually receding into the distance.

This piece is an excellent example of a work that was created as a scientific experiment, but is also successful as an artwork. The aesthetic decisions made by Benton and collaborators resulted in a shining crystalline space, full of colours and visual rhythm, into which the viewer is invited to travel. The perceptual experience of this piece is dazzling and uplifting, as it gives the impression that the grid of rainbow gems is illuminating a phenomenon that is normally invisible, but always present in the physical structure of our world. As one of the most famous holograms, and Benton’s best-known work, the precision and simple elegance of the design position this work alongside pieces by minimalist artists such as James Turrell or Robert Morris.

Figure 11. Steve Benton (1942–2003) - ‘Crystal Beginnings’ 1977, white light transmission hologram (12 x 12”) (Photo by Jonathan Ross)

From the exhibition catalogue:

A scientist with a long and distinguished career in optics, Benton invented the ‘Rainbow’ white light transmission hologram while working at the Polaroid Corporation. It is the basis of all the mass-produced holograms we are familiar with from security devices on credit cards to toothpaste packaging. The technique was adopted by artists in the 1970s and 80s and Benton became director of the Centre for Advanced Visual Studies at MIT and one of the founders of the MIT Media Lab.

Crystal Beginnings is probably Benton’s best known work. Created as a scientific experiment, it was recognized as a work of art by the holographic community and widely exhibited. This copy was first shown in England at the Light Dimensions exhibition at the Royal Photographic Society in Bath in 1983 and subsequently at the Science Museum in London.

Benton’s collaborator Will Houde Walter wrote the following description of the work in 2010.

“Infinity windows are often used in commercial displays, store windows and art pieces in order to create the illusion of depth in a framed picture sized presentation. Crystal Beginnings was an optical experiment in creating a laser

holographic enhanced infinity window. All infinity windows are constructions where light sources are mounted to a mirror and the light is reflected by an adjacent mirror allowing the light to bounce back and forth creating the illusion of depth. The light lost per bounce between the mirrors limits the depth of the effect to just a few inches. Crystal Beginnings, alternatively, used an array of laser pumped fiber optic emitters spaced on one inch centers as the source of the object beam. Multiple step and repeat exposures were made by moving the laser illuminated fiber optic array in one inch steps away from the recording plate for each of the ten exposures.

"Salt Crystal" was the original working title of this hologram. This image created the orderly symmetry of a crystal of Sodium Chloride. One of the key achievements with Crystal Beginnings is that the virtual crystal array appears evenly illuminated and bright at every point in the object. This project took one month of holographic lab time at Polaroid Research in Cambridge, Massachusetts as well as the focused effort of Dr. Stephen Benton, Herb Mingace and myself. Over 100 test exposure plates were recorded in refining the image. We exposed the hologram master plate using a highly coherent 5 Watt Argon Ion laser. This bright green laser was theoretically capable of creating a holographic scene of up to 500 meters deep. The recording was made on a Newport vibration isolation table using Agfa 8E75HD Millimask holographic plates and developed in a proprietary Polaroid holographic film developer based on Vitamin C."

2.12 Iñaki Beguiristain - 'Reflections' (2002)

'Reflections' is a multi-colour reflection hologram on glass. The composition features a grid in the background, with black and yellow squares, and a bright green shifting web-like object in the foreground, which appears to move in swishing gestures that are difficult to discern. The green shape changes dramatically with even the smallest movement, and new details can only be perceived by obscuring other elements, making it difficult to comprehend the form of the central feature.

This work experiments with the possibilities of holographic ambiguity. The green shape is depicted as if it has been captured moving at a rate that is faster than what we can perceive, creating a cloud of energy. The viewer is invited to enter the space and move around, while referencing the grid, and to attempt to classify the nature of the green shape. This work shares an aesthetic quality with some forms of 'net art,' in which space is often represented using grids, and asks us to imagine the technical parameters of the real spaces we inhabit, while considering the perceptual qualities of the virtual spaces in which we increasingly spend our time.

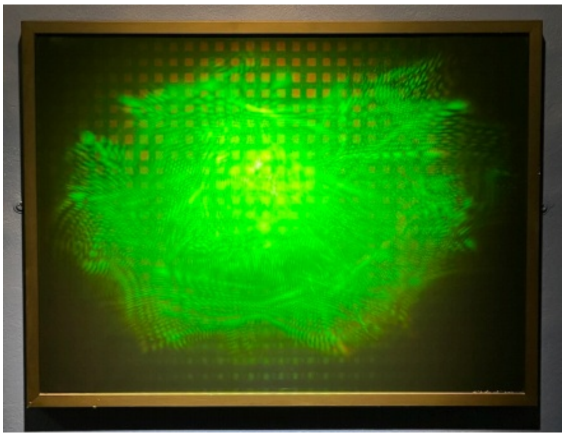

Figure 12. Iñaki Beguiristain (b. 1972) - 'Reflections' 2002, multi-colour reflection hologram (30 x 40 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

Inaki Beguiristain was introduced to holography as a teenager during a visit to an art exhibition in London. Within a few years he had set up a small facility for making reflection holograms and is now regarded as one of the finest practitioners in the country, working worldwide as a consultant.

His focus for the first two decades was predominantly representational work, the idea being not just to faithfully replicate features of an object but to enhance its characteristics, giving the object a new lease of life. Having thoroughly mastered that aspect of the medium, Beguiristain now works more in the abstract, seeing holography simply as a tool to control light. Some of his more recent work combines holography with other photonic sources to give an end result that, for him, is the essence of pure light and its interaction with space.

He has recently built a dedicated holographic facility in a quiet spot of the East Anglian countryside, where he intends to focus further on traditional analogue holography, and what it has to offer.

2.13 Jacques Desbiens - 'Distortions' (2009)

'Distortions' is a full colour digital holographic stereogram, with pastel colours including pink and turquoise. The composition features a number of different shapes positioned around a larger cube, all of which shift in position and colour as the viewer moves from side to side. There are many detailed elements and complex movements represented, and the objects change state according to the position of the viewer.

Jacques Desbiens is interested in the use of holography with respect to movement and image composition. When making this work, he was testing the occurrence of 'time-smear', which is the distortion and blurring of features of objects as they move in holographic space[6]. Like 'Crystal Beginnings', this work was created as an experiment, and emerged as an intriguing composition that is in dialogue with contemporary new media art through its portrayal of a digitally-generated environment that, given new developments in virtual reality, we could potentially inhabit and explore.

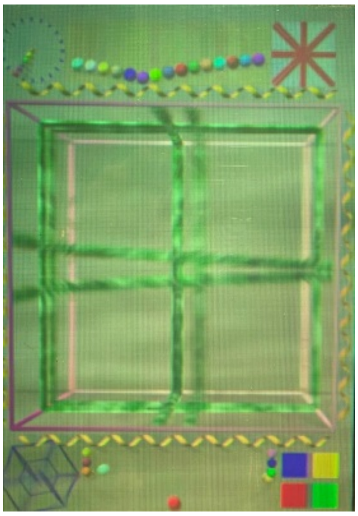

Figure 13. Jacques Desbiens - 'Distortions' 2009, full colour digital holographic stereogram (25 x 18 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

In cinema, content is spread over time. Everybody sees the same things at the same time. Movements and speed are determined by the filmmaker and his camera. The viewers are captive. When content is spread over space, as in synthetic holography, and the observer can freely perceive one or more subjects in a different chronology by moving at his own rhythm, time can be represented only in a symbolic form. There is no "real" time in a synthetic hologram; there is only *the viewer's time of observation. There is no speed in an animated synthetic hologram; there is only the observer's speed of movement.*

(For example) A succession of elements appearing when the observer moves from left to right will reverse itself when the observer moves from right to left. Something opening will close. Something appearing will disappear. Something going down will go up. A waterfall will flow upward. A bird flying will appear to go backwards. An assemblage will be deconstructed.

To visualize some of these visual effects I designed an experimental hologram in which objects are moved in different directions.

Adapted from the artist's paper 'Experiments in image composition for synthetic holography'.

2.14 Amy Rush AKA Holographic Love - 'I'm Spinning Around' (2005)

I'm Spinning Around' is a full colour, mirror-backed digital stereogram. The image shows a woman in white (the artist) spinning through an expansive garden landscape while wearing a white dress. The woman is presented in a realistic way, indicating that the hologram was created using a video of the artist moving in real life, while the background is presented as a highly artificial digital world, with bright colours of the rainbow, pixelated flowers, and a pixelated white horse moving in the background. There is substantial horizontal movement in the piece, and the viewer must adjust their viewing angle to track the changes in the image and composition.

This piece holds an important position in holography history, as it appears to be the first time that an artist was able, using digital holography technology, to insert herself into a virtual environment: a permanent visitor in a world of her own creation. The choice to render the flowers and other elements with a high degree of pixilation emphasizes the degree to which the artist has taken agency in creating the portrayed environment, and also comments on the implied necessity of technological precision in holography to create meaningful work. The use of vivid colours extends the artist's belief in the philosophical importance of rainbows, despite being associated with a 'kitschy' aesthetic. Rush challenges us to consider the conceptual meaning of her work, from a perspective that is simultaneously joyful and deeply existential.

Figure 14. Amy Rush AKA Holographic Love (b. 1980) - 'I'm Spinning Around' 2005, mirror-backed full colour digital stereogram (27.5 x 36.5 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

Amy Rush studied at Sydney's College of Fine Arts and after becoming interested in holography she went to the Center for Holographic Arts in NYC to undertake a one year internship. In 2005 she was offered a fellowship at the Academy of Media Arts, Köln, Germany to work further in the medium of digital holography. Her thesis "Rainbows – The Superhighway of Travel between Material and Virtual Worlds", focused on rainbow holography.

Her work plays with the popular misconception of holograms being copies of their subjects and uses this misconception to create a new authored rainbow reality. The images share the characteristics of a rainbow as well as depicting rainbow imagery, which combined allows you to enter into this world via the reoccurring figure in the work. A kitsch aesthetic with a narrative sharing stories of eternal moments, captured in moving rainbow holography.

In her thesis Rush compares this work with Caspar David Friedrich's Mountain Landscape with Rainbow in which Friedrich uses the phenomenon of the rainbow as a backdrop to a vast emotional landscape with a tiny figure portrayed as a solitary wanderer questioning the sublime in nature, as if for the first time. The viewer of the work is able to take the place of the figure via the method of becoming a witness. "In my work 'I'm Spinning Around', I too use a small figure in a sometimes sublime but disturbing landscape, with the hope that people can enter this dimension via my imagery. In doing so they are able to enter into my psychological reality to experience my ideas as real things".

2.15 Paula Dawson – 'Water Ray' (Study for Luminous Presence) (2007)

'Water Ray' is a computer graphic holographic stereogram mounted on a brown background with a black frame. It features a feminine figure who is looking away from the viewer while surrounded by a mist of vivid purple, orange, and pink shapes, which change with the viewing angle. This work was created as a study for Dawson's piece 'Luminous Presence', which features a similar character and environment.

This piece portrays an otherworldly space, and allows us to imagine what it would be like to experience that space by demonstrating how the atmosphere moves around the central figure. Like Amy Rush's 'I'm Spinning Around', 'Water Ray' shows us how holography can be used to create a completely new environment, and to position individuals into that space in a way that may or may not be relatable to the viewer. We can attempt to imagine the experience of the character because we are able to see how the atmosphere changes around them according to our own movements, thus enabling us to feel connected or immersed in the depicted environment.

Figure 15. Paula Dawson (b. 1954) – 'Water Ray' (Study for Luminous Presence) 2007, computer graphic holographic stereogram (25 x 25 cm) (Photo by Jonathan Ross)

From the exhibition catalogue:

By the time Paula Dawson made the hologram in this exhibition, which typically used cutting edge technology, she had already been involved with holography for 30 years. One of the first Australians to use holography as an art medium, she lost no time in making some of the largest holograms possible at that time and created immersive environments which incorporated them. A flamboyant personality with a dress style to match, Paula is rarely seen without a flower in her hair, she nevertheless acquired an explosives licence and some of her earlier works involved blowing things up.

Increasingly interested in visual effects from traditional Old Master art, for example the use of darkness or chiaroscuro, she wrote in 2004 that "The lack of a large group of practising holographic artists denies the possibility of holographic art work being located within the context of holographic art practice, and it has to seek another context outside its own domain. I have solved this issue in my own work by re-investigating techniques of image making in historical artworks"

Regarding this particular body of work, 'Luminous Presence', she stated that "For many years I have been working toward enabling dialogue between real and holographic (virtual) people. In this work, I'm interested in bringing together elements of the way science fiction films have represented holographic characters and some ancient artistic means of depicting legends and stories of people made from, or surrounded by light, such as ghosts or angels who talk to and influence real people. Consequently, the figures in my holograms are not intended to look like real people. They are designed to look like real holograms! It seems to me that thanks to imaginative directors, script writers, and talented special-effects and CG artists in the film industry, the visual language of luminous transparency of holographic characters is now synonymous with the "real" holographic, autonomous presence of another person."

3. DISCUSSION

3.1 Reception of the exhibition

Among various art mediums, holograms are particularly interactive: it is necessary to physically move around in space to explore the content of the work. That the experience of perceiving the work in real life is so embodied emphasizes the potential for holography in creating artworks that are intimate and personal, and that explore complex ideas. During the open viewings, it was satisfying to watch people interact with the artworks in the exhibition, and to talk about their perceptual experiences. The exhibition was well attended and I was fortunate to be able to meet many holographers and discuss the works at length. However, I found it difficult to promote the exhibition amongst circles of people who were not already part of the holography community, which probably speaks to the enduring negative reputation of the medium in terms of its position in contemporary art discourse. When I was able to attract younger artists to the exhibition, they were frequently surprised to learn that holography is accessible to them, and were curious about accessing the resources needed to make new holographic work. I was happy to be able to refer them to some of the new initiatives for online education, such as those offered by the International School of Holography. However, to develop a thorough understanding of the possibilities of holographic expression, it is essential to be able to experience some of the incredible works that have been created throughout the history of this artform. Thus, further exhibitions are needed, with curatorial practices that are in dialogue with contemporary art, to increase the visibility of this important medium for artistic expression.

3.2 Conclusions

My goal with this exhibition was to facilitate a rare opportunity to experience transformative works from a selection of holography history, in a moment when global centers for holography education, exhibition, and practice are in decline. Paradoxically, recent technological advances have made the process more accessible than ever: the materials required to make holograms, such as lasers and photopolymer film, are relatively affordably and increasingly available. By celebrating the unique expression of these important figures in the history of holography, it is my hope that this exhibition will encourage both artists and scientists to attempt new holographic works, and to invite members of the contemporary art community to consider the potential of this medium for creative expression. I am very grateful to Jonathan Ross for this opportunity, and am excited to continue educating myself about the colourful history of holography. For those who wish to observe the movement within the holograms, a video of the exhibition will be made available online.

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APPENDIX: CURATORIAL STATEMENT

Like the many forms of contemporary art that we are now used to seeing—but not beholding—on screen, holograms require our embodied experience to be fully perceived. With a depth and dimensionality corresponding to that of digital virtual reality, when confronted with a holographic image, we must move our bodies to discover a world that is not immediately visible. Holography asks that we exist simultaneously: to experience the virtual world created by the artist, we must also be IRL, where our bodies search and swipe, manipulating the motion, time, and visual qualities of the hologram. This duality of experience offers critical insight in this moment, when we all must address the tangible and conflicting demands of diplomacy and crisis, which are affected and even created by the online virtual worlds that we increasingly inhabit.

This exhibition looks back through holography from the late 1970s to the early 2000s, and celebrates the spirit of generosity and mind-expanding adventure shared by the artists of the international holography community. As a guest curator in the Jonathan Ross collection, I have specifically chosen to present holograms that illustrate the range of possibilities for personal self-expression, world-building, and shape-shifting: Susan Cowles' House of Moons (A Stage for the Chymical Theatre) (1988), which contrasts the technical brilliance of a hologram with a lively ink on paper frame to depict human cognition as a psychedelic theatre; Amy Rush's vibrant digital hologram I'm Spinning Around (2005), with its newly constructed Alice among the talking flowers-type world; works that connect historical artefacts to contemporary conversations, like Harriet Casdin-Silver's stunningly body-positive Venus of Willendorf (1991), originally featured on the cover of Sculpture magazine; and works by 12 other international artists, whose meanings are connected, materially and conceptually, to the specificity of holography as a medium.
As a technology with many early applications in politics, medicine, and business, holography holds incredible potential for artists, who have historically overcome the demands of equipment and expertise to create highly intentional work. Although artists working in other mediums have discovered holography's potential (such as Louise Bourgeois and James Turrell), contemporary holography has not been widely exhibited and, like performance art, holds unique challenges to documentation.

This exhibition offers a rare opportunity to experience transformative works from just one possible history of holography, in a moment when global centres for holography education, exhibition, and practice are in decline. Paradoxically, recent technological advances have made the process more accessible than ever: the materials required to make holograms, such as lasers and photopolymer film, are relatively affordably and increasingly available. By celebrating the unique expression of these important figures in the history of holography, it is my hope that this exhibition will encourage any one of us to attempt our own holographic works, so that we may invite others into our future as-yet-invisible worlds.

TRACK 2.

Color Holography

Fill-factor analysis for the augmented reality system using the full-color holographic optical element micromirror-array

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ABSTRACT

This paper proposed a fill factor analysis of the full-color holographic optical element micromirror array (HOE-MA) using in the holographic waveguide for a 3D augmented reality display. The system has two holographic optical element films on the in-and out-coupler of the holographic waveguide. The fabricated full-color HOE-MA acts like an optical mirror lens array and is placed in the in-coupler. The size of the optical mirror lens array is 1x1mm. In the experiment, each lens was recorded with a slight overlap. Because, if the optical mirror lens array is recorded in the recording area with the same size as the original size of optical mirror lens array, the HOE-MA size is recorded as 0.9 mm, causing a dark spot. Noticed that the image quality was reduced when reconstructing part. Therefore, the fill factor of HOE-MA was calculated and recorded. Reconstructed 3D images and real objects are through this system were visible to the observer's eyes.

Keywords: Holographic optical element, Microlens array, Augmented reality, waveguide

1. INTRODUCTION

Three-dimensional (3D) displays can offer more real images to observers with depth information that is absent in two-dimensional (2D) displays. Recently, autostereoscopic 3D displays based on a parallax barrier or lenticular lens array for presenting binocular disparities have received much attention due to the convenience of achieving 3D visual effects without the need for augmented reality (AR) glasses. The AR displays have to see-through feature that any virtual computer-generated perceptual items are observed and controlled in the real-world environment without using the hands, instead of the user that is completely sequestered from the real-world. Here, the information of the digital elements can be added into the real-world [1]. Every real-world object has 3D which are the width, height, and depth information. However, in development of 3D displays, since most of the content is still based on 2D images for 2D display panels, the mode convertible function between 2D and 3D conditions is an essential requirement and can be achieved using switching optical elements [2].

For the AR display system using many methods creates that system. Compared to other types of waveguides, the advantages of the holographic waveguide technique are the small volume, low price, and suitability for angular and spectral selectivity of holographic optical elements (HOEs). There are two main optical parts are existed in the holographic waveguide: in- and out-couplers which are the HOEs. The in-coupler part reflects the micro-display's image, and the out-coupler part transmits the image to the observer eye where waveguide transmits the light beams between two HOEs. The conventional holographic waveguide propagates in the light entering the waveguide with specific angle due to the use of holographic volume grating (HVG). Thus, the entering light travels through the waveguide according to the total internal reflection and is directed to the eye with the order HVG. The 3D screen using the lens array with reflection type HOE have been published recently [3-7].

For the 3D image generating methods are few but the integral imaging is a practical lens array-based 3D imaging technique and consists of the two main processes: the pickup and display. In the pickup process, an elemental image set (EIS) is captured from the given 3D object via the lens array by imaging the light rays reflected from the object, where each corresponding elemental lens samples the 2D perspectives with different viewpoints from their respective overlooking locations. The maximum number of elemental images is limited by the number of the elemental lenses, and the overall size of the entire EIS is the same as the size of a lens array. As mentioned earlier, the full 3D information of the object is kept in the EIS. During the reconstruction, the 3D visualization of the object is reconstructed from the captured EIS, through the same lens array used in the pickup part. This reconstructed 3D image is observed in the space in front of or behind the lens array, so it can be seen as a volumetric 3D image, because it is reconstructed around the region of light rays. The intersection where the light rays are coming from the EIS and refracted after directly passing through a lens array [8].

While the active barrier method using a liquid crystal (LC) cell easily offers the 2D/3D switching function, brightness degradation inevitably occurs in 3D mode images compared with 2D mode images because the active barrier method simply controls the directional transmittance levels of the panel images to form binocular disparities. The switchable liquid-crystalline (LC) lens has been extensively studied for 2D/3D switchable displays, integral imaging 3D displays, an integral imaging endoscope [9]. To develop an AR system using a switching LC-MA, the switching LC-MA should be implemented with improved optical properties that include a high fill factor, small f-number, small focal ratio, and square-type 2D MLA shape. Recently, Kim et al. demonstrated a polarization-dependent switchable liquid-crystalline polymer (LCP) lens array developed with improved electro-optical properties, specifically a small f-number, high fill factor, low driving voltage, and fast switching speed, using well-aligned reactive mesogen (RM) [10] on the imprinted reverse shape of the lens and a LC-based polarization switching layer. The developed lens can be implemented on a flexible substrate as a stack structure with several RM lenses. It has been confirmed that this type of lens is particularly suitable for microdisplays. Despite recent interest and active research in the optical see-through AR, most of reported optical see-through AR systems provide 2D and 3D virtual images, being able to display 3D virtual images. However, several research groups have recently presented optical see-through AR systems supporting the 3D virtual images [11-16].

In this paper, the improvement of fill factor of HMA with holographic waveguide-type for 3D AR display system.is proposed. Here, the EIS is displayed by the micro-display, through to the holographic waveguide, reconstructed 3D image reflected on the in-coupler HOE which fabricated HMA. Then relayed to the in-coupler HMA which satisfies the Bragg matching conditions and transmitted to the out-coupler HOE through the waveguide. The proposed system has an additional critical advantage that the observer can see the realistic 3D visualizations reconstructed by the proposed method. In the experiment, the AR feature has been successfully verified that the real-world scene and reconstructed and 3D image were observed simultaneously.

2. PROPOSED METHOD

Figure 1 presents a schematic configuration of the proposed 3D holographic waveguide-type AR system using the holographic waveguide with HOE. The main structure consists of microdisplay, fabricated HMA and holographic waveguide with HOE. In the proposed system, the HMA is used with the single projection method. Here, the EIS is displayed by the micro-display to holographic waveguide, then the reconstructed image reflected in the in-coupler HOE which is HMA, transmitted the images into the waveguide and the reconstructed 3D images are travelled through the waveguide. The out-coupler HOE transmits the reconstructed images shown in the observer eye by reflecting in the out-coupler HOE. Because an in-coupler HMA has a similar role for image forming properties with the lens array, but the light beams are reflected on each mirror and reproduce the 3D image like lens array-based integral imaging technique, where each fabricated lens array HOE. Also, Proposed method main setup: the fabrication for the HOEs, in-coupler HOE is our main fabricated HMA, and out-coupler HOE, and implementation of the AR display using the fabricated HOEs. Note that the HOEs should be fabricated as the reflection-type. The HOEs are recorded as following the hologram recording system, but HOEs incident angles are different.

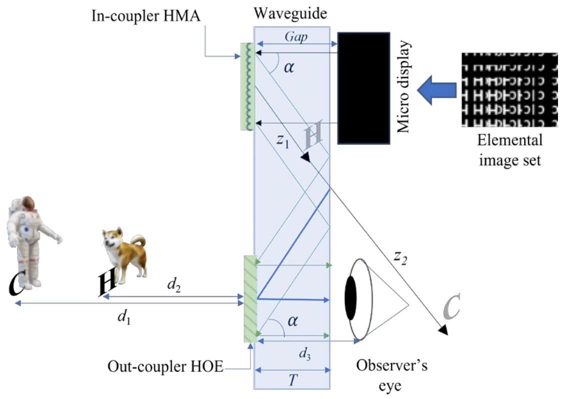

Figure 1. Holographic 3D image for AR display system using the holographic waveguide-type with HOEs.

3. EXPERIMENTAL AND RESULT

In the experiment, a diode-pumped solid-state He-Ne green laser with 532 nm wavelength, the collimating lens with 200 mm focal length that adjusted for green laser, the electrical shutter, the polarizing beamsplitter and mirrors. The BAYFOL HX 102 photopolymer was used as the HOEs.

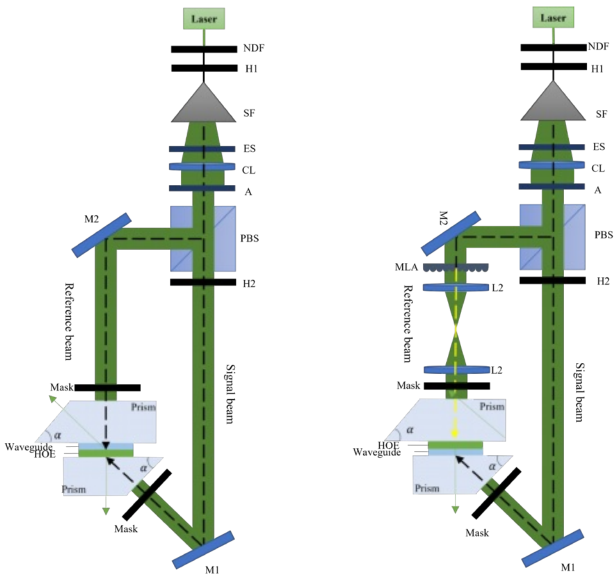

Figure 2. Schematic representation of the in-coupler HOE which is fabricated HMA and the out-coupler HOE recording setup.

4. CONCLUSION

The waveguide-type 3D AR display system based on the integral imaging technique using the holographic waveguide-type system is proposed. Unlike the conventional AR displays, the fabricated HMA is placed front in of the waveguide with a stick. Thus, the HMA has a function that is the same as the micro lens array, reconstructed 3D images are reflected into the waveguide and the reconstructed image was transmitted by out-coupler HOE in front of the observer's eye. The experimental result confirmed that the real-world scene was observed with the reconstructed 3D image at the same time. The advantages of conventional holographic waveguide such as thin-size and lightweight, are kept in the proposed system. The 3D image was displayed through the proposed system without required any additional device such as collimating lens, prism, consisted of the main devices of the conventional holographic waveguide-based AR display (the microdisplay and holographic waveguide with two HOEs). The HOEs have the function that reconstructs the 3D image in front of the observer's eye.

ACKNOWLEDGEMENTS

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Characteristic of printed holographic screen with speckle pattern

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ABSTRACT

The holographic stereogram printer records a multi-view three-dimensional image, interfering with the reference wave and the object wave with angular intensity distribution and recording it onto the holographic emulsions in hogel unit. In a similar way, a holographic screen can be produced by recording an object wave with arbitrary angular intensity distribution characteristics using diffuser as a hogel. The coherent laser used to record the holographic screen generates a speckle pattern, which generally acts as a factor that degrades the image quality. However, the high luminance characteristics of the speckle pattern have the advantage of increasing the brightness of the image. Through this, a holographic screen with a speckle pattern may be used in outdoor advertisements or promotions. In this paper, a holographic screen with a speckle and a holographic screen without a speckle were produced under the same conditions and luminance characteristics of the two screens were compared, and the applicability of the speckle pattern was confirmed.

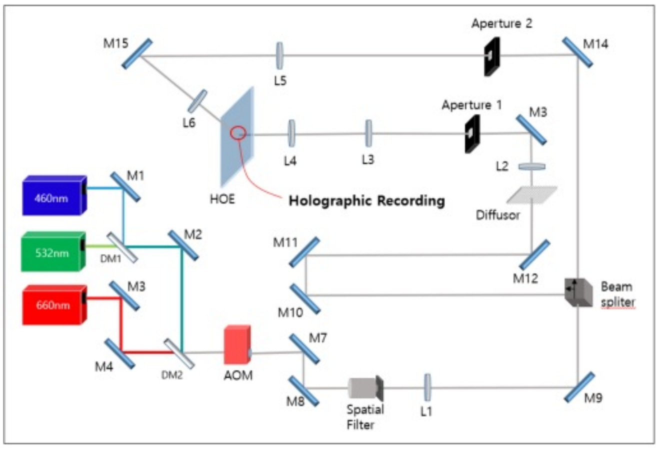
Keywords: Speckle pattern, holographic stereogram printer, angular intensity distribution, arbitrary angular intensity distribution, hogel, diffuser, speckle noise, holographic screen

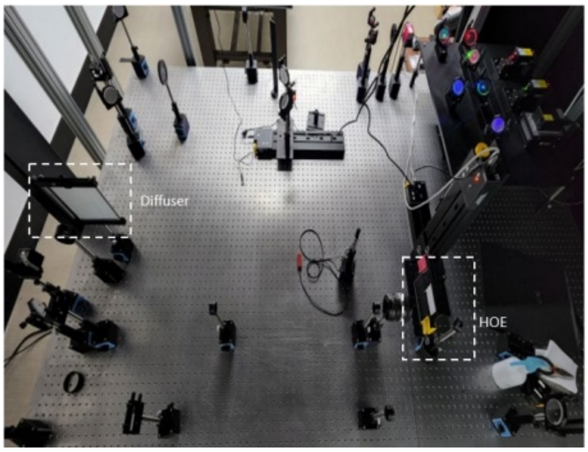
1. INTRODUCTION

Holographic stereogram printing is a technology that can record three-dimensional content and display high-quality three-dimensional images based on binocular parallax [1]. The object wave used in the holographic stereogram printer contains a recombinant image of the objective image taken at each point in time, and is recorded in the holographic techniques by interfering with the reference wave as a hogel image with angular intensity distribution. The recorded hologram can feel depth and three-dimensional effect from various angles. The holographic screen is a holographic diffuser using holographic stereogram printing technology. The hogel image used in the holographic screen has the characteristics of a uniform angular intensity distribution. It is possible to produce a holographic screen by recording using object wave with this distribution. The holographic screen may be used for a transparent display such as a window or a car head-up-display (HUD). However, in general, when producing holographic screens, a rapidly changing random phase distribution is used to reduce speckle noise. In this case, grating with low clarity may be recorded due to the rapidly changing phase distribution in the process of entering and recording light to record the hogel. As a result, the diffraction efficiency of the printed holographic screen has a low distribution, and it is difficult to observe clearly in outdoor environment [2,3]. To overcome such bottleneck, we tried to use a holographic screen with speckle pattern and coherent light source to increase speckle effect.

Speckle patterns mainly occur in optical lasers with coherence characteristics. Optical lasers emit beams of constant and continuous frequencies. Coherent beam reinforces and offsets the intensity inside, resulting in a certain pattern of bright and dark, which is observed to speckle in our eyes because it is always maintained in the same phase due to the coherence of the laser. This is called a speckle pattern. In general, the speckle pattern acts as a factor that degrades the image quality. However, when used in advertisements or promotion, such speckle patterns have the advantage of increasing special effects and brightness, so they can be applied to holographic screens in consideration of these characteristics. This paper aims to increase the utilization of speckle patterns through these attempts.

2. EXPERIMENT AND ITS RESULT





(a) (b)

Figure 1. (a) Schematic diagram of an optical system for holographic screen recording. (b) Setup of an optical system for holographic screen recording.

2.1. Holographic screen recording optical system configuration

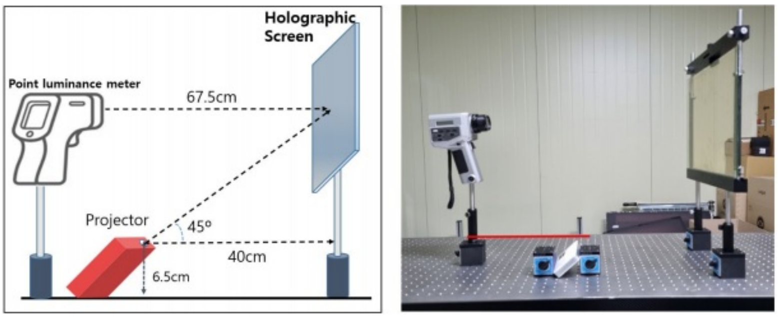
Fig. 1(a) shows the structural diagram of the implemented optical system to record a holographic screen with speckle pattern. This system also can record a holographic screen without speckle pattern by diffuser rotation. Lasers in wavelengths 460 nm, 532 nm, and 660 nm are used as light sources. Each beam of red, green, and blue is combined to form a white beam by using mirrors M1, M2, M3, M4, and dichroic mirrors DM 1 and DM 2. The white beam passes through the acousto-optic modulator (AOM) and spatial filter. The AOM is used as optical switch to control the beam exposure time on a holographic emulsion. Optical noise is removed through the objective lens and spatial filter, and collimated by the lens L1. The collimated beam is separated into an object beam and a reference beam by a beam splitter.

The object beam is reflected by mirrors M10 and M11 and serves to match the optical path length between the object beam and reference beam. The beam reflected by the mirror M12 passes through the diffuser to uniformize the intensity distribution of the beam. The beam passing through the diffuser is converged by a lens L2 with a focal length of 100 mm, and passes through the first square Aperture 1 with 2.5mm × 2.5mm size. After Aperture 1, the beam size is magnified by the lens L3, L4 to illuminate on the holographic emulsion. The focal lengths of lens L3 and L4 are 50 mm and 500 mm, respectively.

The reference beam is reflected by mirror M14 and passes through Aperture 2. The beam passing through Aperture 2 is reimaged to the photo-refractive medium by reducing the shape of aperture 2 through lens L5 and L6. The focal lengths of lens L5 and L6 are 75 mm and 750 mm, respectively. The magnified beam size is about 250um × 250um. The angle of incidence reference beam can be adjusted by the mirror M15. The incident angle of the reference beam was set to angle of 45 degree. A photopolymer is utilized to record a holographic screen by the implemented printing system. This material is mounted on the x-y moving stage. The implemented optical system is shown in Fig. 1(b).

2.2. Comparison of holographic screens

The implemented holographic screen recording system, as shown in Fig. 1, can produce a screen with speckle patterns as well as screens without speckle patterns. As mentioned above, speckle pattern can be removed by rotating diffuser. The transparent image projection system with the recorded holographic screen is implemented to measure corresponding display qualities, and the corresponding schematic and image are shown in Fig. 2. As shown in Fig. 2(a), the holographic screen manufactured by recording in a hogel unit is mounted perpendicular on the optical table, and the beam projector projects at an angle of 45 at distance of 40 cm from the holographic screen. The luminance of the displayed image was measured using a point luminance meter. The point luminance meter was located at distance of 67.5 cm from the holographic screen. Fig. 2(b) shows the system built according to the experimental composition diagram. The luminance for the two screens, one is with speckle and the other one is without speckle, was measured by the point luminance meter.



(a) (b)

Figure 2. (a) schematic diagram of the measurement environment for measuring the luminance of the holographic screen. (b) experimental setup for measuring the luminance for the holographic screen.

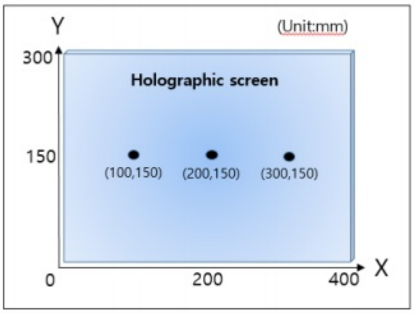
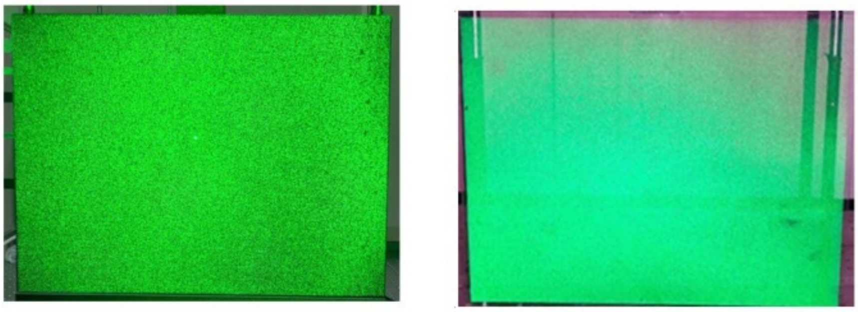


Figure 3. Coordinate for the measuring point location on the holographic screen. Three coordinates were selected on the holographic screen to measure luminance.

For experiment, an image with uniform intensity distribution is project by the beam projector as shown in Fig. 2, and the projected luminance is measured by the point luminance meter at the desired three points. At that time, the recorded two different screens are applied in this experiment, and the measured results for each screen are described in Table 1. As shown in Table 1, the luminance for the holographic screen with the speckle was about 1.23 times higher than that of the holographic screen without the speckle. Accordingly, it may be confirmed that the holographic screen having a large number of speckle patterns has relatively higher diffraction efficiency than the other case.

Table 1. Measured luminance values for each holographic screen at desired measuring locations.

	Measuring location (X, Y)	Luminance (cd/m^2)	Average of luminance (cd/m^2)
Screen with speckle pattern	100,150	122	120
	200,150	124	
	300,150	114	
Screen without speckle pattern	100,150	99.4	97.5
	200,150	99.7	
	300,150	93.4	



(a) (b)

Figure 4. (a) projected green image on the holographic screen with speckle pattern (b) projected green image on the holographic screen without speckle pattern.

Fig. 4 shows the projected images on two different screens, respectively. As shown in Fig. 4, in the case of a screen without a speckle, an image with uniform intensity distribution could be obtained as expected, and in the case of a screen with a speckle, the speckle pattern was highlighted. Depending on the video content, the speckle pattern may act as noise, but in the field of outdoor advertising and promotion that requires high luminance, a screen including the speckle may seem more suitable.

3. CONCLUSION

In this paper, the possibility of using holographic screens containing speckle noise was confirmed. First, holographic screens containing speckle patterns may be suitable for fields that increase outdoor advertising and visual effects because of their high luminance characteristics. Second, cost is reduced because no additional equipment is needed to eliminate speckle noise. Third, holographic screens containing a speckle pattern can be more noticeable to the human eye, which can be helpful for promotion. Due to these features, holographic screens are expected to be of great help in various applications.

ACKNOWLEDGEMENT

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The ZZZyclops V2 color holography system

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ABSTRACT

We present the new version of the Hellenic Institute of Holography transportable color Denisyuk holograms recording system which we developed during 2020. The ZZZyclops V2 system is the successor of our Z3[RGB] color holography system, which was firstly introduced during ISDH2012. The system is suitable for recording Denisyuk-type color holograms on silver halide or photopolymer holographic plates. The ZZZyclops V2 camera has three TEM00 DPSS single frequency lasers with wavelengths at 457nm, 532nm and 640nm and powers of 200mw, 500mw and 500mw respectively. The system can be easily transported inside any room in a museum for in-situ recording of high quality color holograms of valuable items.

Keywords: Color holography, OptoClones, holography museum applications, HiH

1. INTRODUCTION

The Hellenic Institute of Holography (HIH) was established in Athens in 1987 with the purpose of introducing and promoting Holography in Greece and abroad in all possible areas: science, art, media and authentication. HIH has the status of non-profit scientific and educational organization with its income derived by members' contributions and services to third parties. Being active in a country with a unique cultural tradition of worldwide influence extending from Classical Ancient Greece to Orthodox Byzantium Christianity, the use of display holography in the preservation, recording and public visual dissemination of artifact items of cultural heritage has been at the core and forefront of the activities of the Hellenic Institute of Holography. In this framework, during the period January 1995 until end of April 1996, HiH participated in the project "Holography applied to protection, preservation and non-destructive evaluation of cultural heritage" funded by EU IC-INTAS 93-2779 program. The program was coordinated by Prof. Pierre Boone of Gent Universiteit (Belgium) with participants the National Academy of Sciences of Ukraine (Prof. Vladimir Markov), the Russian Academy of Sciences (Prof. Yuri Denisyuk) and HiH (Greece).

An excerpt from the project's objective[1]: "*Holography offers extraordinary potential applications in the domain of cultural heritage. Two main trends exist. One is that of display holography, where holograms are used as a means of visual information representation, for example, to exhibit* ***optical copies*** *of museum items. The second direction is connected with technical applications of holography and can be used to solve problems related to the study, conservation and restoration of museum items, e.g. by checking the present state of integrity of objects and locating and characterizing deterioration before it becomes critical* ".

Building on the experience gained during this program, the HiH holography lab started experiments on optimizing techniques and hardware for the holographic recording of museum artifacts inside museums without the need of a typical holography laboratory, especially without the need for bulky and heavy weight optical tables. Considering museum security policies, it was clear that mobile recording equipment was necessary in order to make display holography acceptable as an advanced optically documenting technique to be performed inside museum buildings. More than ten years later (2009), on the grounds of technological progress in various disciplines such as solid-state lasers, panchromatic emulsions, LED illumination etc., the Hellenic Institute of Holography set out its own *HoloCultura* program for the use of color display holography in applications related to cultural heritage. During the first stages of the *HoloCultura* project we identified the Denisyuk-type of color holograms, with their inherent optical properties and the simplicity of their recording layout, as the most suitable type for the holographic recording of valuable artifacts inside museums. Focusing on the development of portable recording equipment and special LED lighting fixtures for the optimal recording and display of color holograms, we developed the Z3[RGB] portable recording system and the proprietary HoLoFoS illuminating devices.

2. ZZZYCLOPS V2 SYSTEMS DESIGN CONSIDERATIONS

In theory, true-color Denisyuk-type holograms of high quality can be recorded in silver halide emulsions or photopolymers and subsequently be displayed reproducing ultra-realistic three-dimensional images, if certain prerequisites are fulfilled e.g. :

- Suitable selection of three or more laser wavelengths
- Panchromatic recording plates with extremely low scattering
- Optimized processing of the exposed plates
- Suitable recording geometry to eliminate dispersion
- Mechanical and thermal stability during recording
- Optimized illumination of the color hologram in order to enhance depth reconstruction, color rendition and to minimize visual blur.

Moreover the design of a mobile holographic camera for the recording of high quality color holograms inside a museum introduces more functional challenges to the overall optical and mechanical design of such a system. Based on the above prerequisites, HiH developed during 2010 to 2012 the $Z3^{RGB}$ transportable color holograms recording system and the novel HoLoFoS LED lighting fixtures, which were first presented during the 9th International Symposium on Display Holography[2]. In a holistic approach to color holography for cultural heritage applications, from the very beginning, we considered that an enhanced illuminating device is an indispensable pair to a high quality color hologram as -in essence- it can be considered as a 2-part system. We have termed the *tuned pairs* of our color holograms and the HoLoFoS™ illuminating devices as **OptoClones™** not only because the holographic image reconstructed from such pairs is ultra-high realistic but also in order to distinguish our derived works from the increasingly incorrect use of the word “hologram” in contemporary so-called “hologram” applications. The original $Z3^{RGB}$ system and the HoLoFoS lighting devices were successfully used in application projects in the area of color display holography for cultural heritage by recording a large number of OptoClones™ of valuable artifacts including the Faberge Eggs collection of the Faberge Museum in St. Petersburg[3] (figure 1).

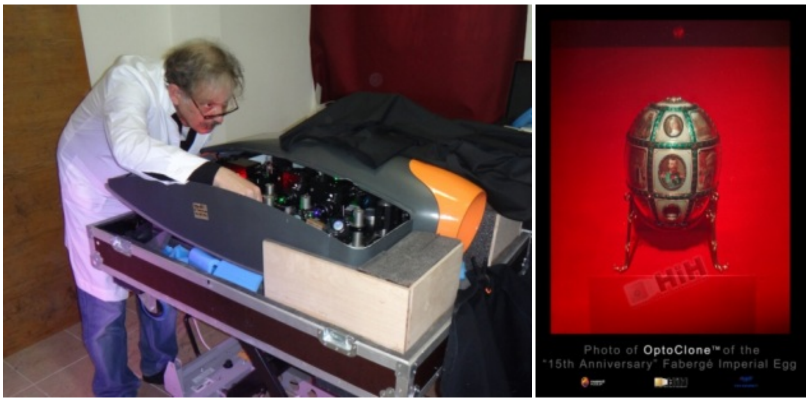

Figure 1. A. Sarakinos adjusting the ZZZyclops V1 camera and the recorded OptoClone of the "15th Anniversary" Faberge Imperial Egg. Spring 2015, Faberge Museum, St. Petersburg.

The proven on the field operability of the original $Z3^{RGB}$ system and the approval of the produced OptoClones by the curators of significant museums' collections led us to redesign the $Z3^{RGB}$ system's camera incorporating more powerful DPSS lasers, which drastically reduce the exposure times either for silver halide or photopolymer materials. The development of the new ZZZyclops V2 color holography system and accessories was carried out during the COVID years 2019-2021, a technical achievement in itself under the extreme restrictive conditions imposed by the pandemic.

Interestingly, the development of this new system came as a deliverable to a public-tender by our long-standing scientific partner in Russia, ITMO University in St. Petersburg, for the procurement of such a portable device. This was deemed necessary from their part in their longer-term research strategy as the successful implementation of high-visibility and highly-praised documentation projects involving national State-treasures and other artworks in 2017 at the Moscow Kremlin Diamond Fund required the local availability of such infrastructure. Subsequent international political developments and trade restrictions greatly justified their original decision and substantial investment.

Of the above listed prerequisites we will elaborate on wavelengths selection, mechanical and thermal stability and reconstruction illumination as they are key factors in the design of a portable recording system as the ZZZyclops and an optimized illumination device for color holograms display as the HoLoFoS[11].

2.1 Selection of wavelengths

The perception of color is formed in our brain by the superposition of the neural signals from three different kinds of photoreceptors which are distributed over the human eye's retina. The human eye has three types of photoreceptors (called cone cells) for photopic vision, with sensitivity peaks in short (S: 420–440 nm), middle (M: 530–540 nm), and long (L: 560–580 nm) wavelengths (figure 2). Thus in contrast to most mammalians that have two types of cones (dichromats) the humans are trichromats. If monochromatic radiation irradiates the eye, as it is the case with spectral decomposition of white light, the wavelength determines which types of cones are excited. For instance, monochromatic light at 680 nm exclusively excites one type of cones, whereas the two other types are insensitive at this wavelength. The brain interprets signals from only this type of cones - in the absence of a signal from the other cones - as the color "red". Similarly, for a monochromatic light at 430 nm that excites only the S cones the brain interprets this type of cones signals as blue. Depending on the response spectrum of the S,L,M types of cones to a monochromatic spectral stimuli certain wavelength might predominately excite a single type of cones, thus producing the color perception of "blue", "green" or "red", but monochromatic light might also excite two types of cones simultaneously, thus producing the perception of another color. Electromagnetic radiation at 580nm that falls on the retina will excite both the M and L types of cones but not the S cones so the only signals generated by the M and L cones will reach the brain producing the color perception of "yellow" but the same color perception can be produced by broadband radiation between 550 nm and 700 nm as long as M and L cones are comparably stimulated and S cones are not stimulated at all (figure 3).

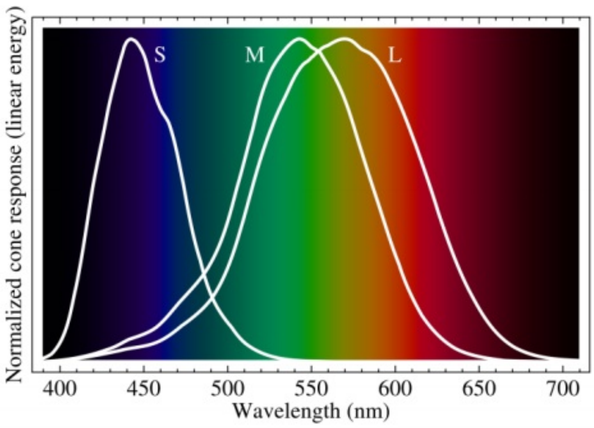

Figure 2. Normalized response spectra of human cones, to monochromatic spectral stimuli, with wavelength given in nanometers.

Thus, in principle, three parameters describe a color sensation. These tri-stimulus values of a individual color can be conceptualized as the coordinates of three primary colors in a tri-chromatic additive color space like the CIE XYZ. In colorimetry, metamerism is a perceived matching of colors with different (non-matching) spectral power distributions. Colors which match in this way are called metamers and this phenomenon led to the design of additive color systems like color television.

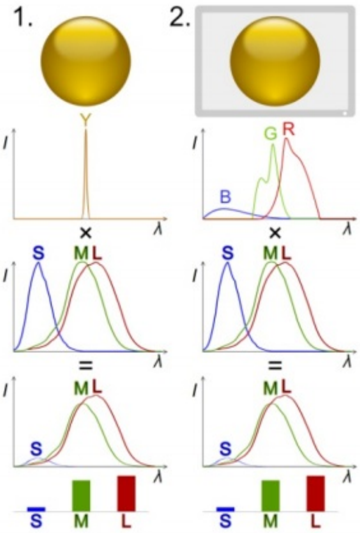

Figure 3. Illustration of color metamerism: In column 1, a ball is illuminated by monochromatic light. Multiplying the spectrum by the cones' spectral sensitivity curves gives the response for each cone type. In column 2, metamerism is used to simulate the scene with blue, green and red LEDs, giving a similar response. (Drawing by cmglee, Vanessaezekowitz - Cones SMJ2 E.svg, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=94744983).

In this aspect researchers in color holography have aimed at choosing three or more suitable wavelengths for recording a color hologram, which would cover a sufficient area of the CIE chromaticity diagram. The same principle can be applied in the design of an RGB-LED illuminant for the hologram “replay” such as the HoLoFoS with coaxial mixing of the three beams and adjustable intensity control of each beam[11]. Thornton[4] found that the reflectivity of an object at three well-specified wavelength bands (near 450, 540 and 610nm) has a disproportionately high color rendering index. Using these wavelengths, a wide range of highly saturated colors can be produced. Hubel and Ward[5] in 1989 recorded color reflection holograms using 647, 528 and 458nm lasers with a wide color gamut. In 1991 Hubel and Solymar[6] found another good practical choice of wavelengths in using a combination of 442, 532 and 633nm. Bjelkhagen and Mirlis[7], Peercy and Hesselink[8] and Kubota et all[9] claim that more than three wavelengths are needed for true color rendition. In ZZZyclops V1 we used two DPSS lasers at 457 nm and 532 nm and a TEC-stabilized DL at 639 nm while in our new ZZZyclops V2 holography camera we use three DPSS lasers at 457 nm, 532 nm and 640 nm.

This combination of wavelengths gives a gamut (figure 4) that includes yellow, purple, dark blue and violet as the Hubel and Ward one, and overlaps the Wintringham locus of extreme purities which according to Wintringham " *there seems to be no indication that any colors found in nature lie outside the locus*" in his milestone paper on tri-color television published seven decades ago[10].

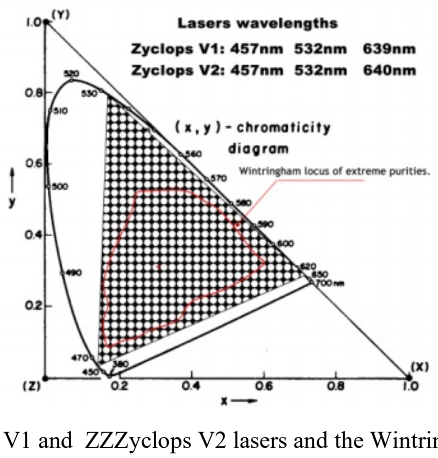

Figure 4. Color gamut of the ZZZyclops V1 and ZZZyclops V2 lasers and the Wintringham locus of extreme purities.

An important factor for this specific selection of wavelengths for our ZZZyclops camera has been the aim to achieve to the extent possible a close match to the spectral response of the human eye and the emission characteristics of available red, green and blue LEDs to be incorporated in the HoLoFoS hologram illuminating devices (Table 1).

Table 1. Wavelengths of the HoLoFoS-λ LEDs.

Color	Dominant wavelengths (nm)
Blue	450-465
Green	520-535
Red	620-640

2.2 Mechanical and thermal stability during recording

It is well established that mechanical vibrations, air currents, thermal expansions or laser wavelength drifting and mode-hops during a hologram recording can result to reduced brightness, banding or to totally destroy the recording. Although the Denisyuk setup (single-beam layout) is less susceptible to mechanical disturbances, we prefer to isolate the object and the plate from floor vibrations using our two-tier isolation system, which consists of a wooden platform on inner tubes on which we further place a thin aluminum optical breadboard sitting on short Sorbothan feet. In order to minimize the effects of mechanically-induced movements of the object relative to the recording plate or vice versa, we designed a new series of custom-made boxes for accommodating the object while acting as plate holders at the same time (figure 5). These boxes offer an adjustable depth in order to accommodate objects of various sizes. We also use a foldable light-proof tent chamber (typical dimensions 2x2x2 m) which encloses and largely isolates the object/plate space in order to minimize air currents, to ensure thermal stability and to permit secluded working in any available room in a museum. The isolation system, plate-holder boxes and the tent chamber are integral standard parts of the ZZZyclops system. Moreover, in order to secure the lasers stability, apart from the manufacturer's provisions for stable operation, it is imperative to ensure proper thermal management of the heat dissipated by the lasers or any other heat generated by dissipating components inside the ZZZyclops enclosure.

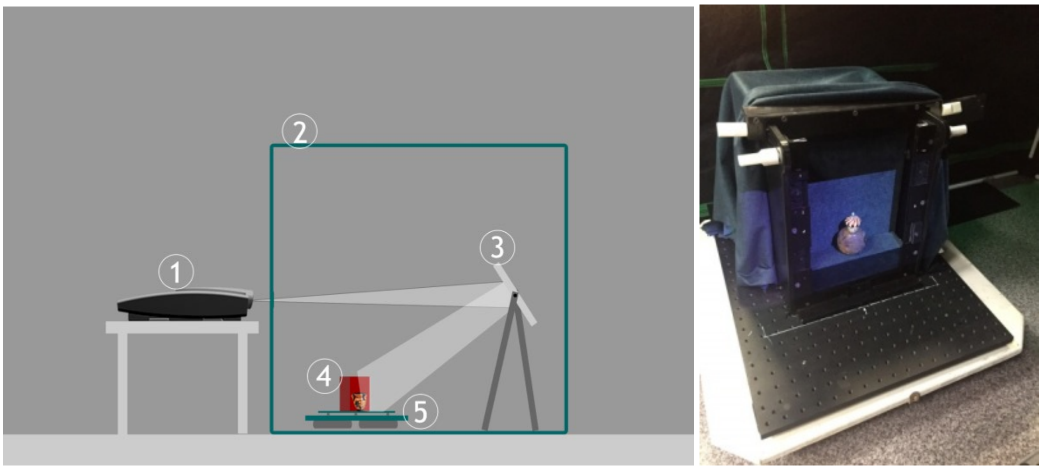

Figure 5. Drawing: a typical setup in a museum's room; (1) ZZZyclops V2, (2) The lightproof tent chamber, (3) Beam steering mirror on a tripod, (4) Object-Plate box, (5) Two-tier passive isolation platform. Photo: the actual Object-Plate adjustable box inside the tent chamber .

2.3 Optimized illumination of a color hologram

The choice of proper illumination sources for the reconstruction of color reflection holograms is of great importance. Assuming that there are no distortions caused by the after exposure processes, a perfect reconstruction theoretically can be achieved if a color-reflection hologram is illuminated by the same lasers and at the same geometry as used during recording. In all other cases the finite dimensions and the spectral characteristics of the illuminating source introduce various levels of image blur, color shifting and scatter noise. When using a tungsten halogen lamp only a small part of the emitted light contributes to the image intensity whereas the rest and larger part is scattered lowering the image's contrast. An acceptably good approximation to the perfect reconstruction can be achieved using LEDs with dominant wavelengths which match the frequencies of the lasers used during recording, small chip sizes and narrow bandwidths[11] .

The finite angular size of an illuminating source produces an image blurring that is equal to the angle that the source subtends at the hologram. If the source subtends an angle θr and the distance of an image point from the hologram's plane is *D*, let δ be the lateral blurring of the image point, then the angular blurring is

$$\theta r = \frac{\delta}{D} \qquad (1)$$

and

$$\delta = \theta r D \qquad (2)$$

So the lateral blurring due to the finite source size increases with θ_r and the distance of the image point from the hologram's plane. For a fixed image point at distance *D* the blurring δ will vary inversely to the source's distance from the hologram's surface and proportionally to the source's extent. The small spatial extent of LEDs chips assists in minimizing the source size blur.

Illumination of a hologram with a very small source of finite spectral bandwidth $\Delta\lambda$ results in a chromatic blur $\Delta\chi$ for an image point located at a distance *D* from the hologram's plane:

$$\Delta\chi = D \sin\theta i \frac{\Delta\lambda}{\lambda} \qquad (3)$$

where λ the wavelength of the recording beam and θ_i the angle of the reconstruction beam relative to the hologram. Equation (3) implies that for a broadband reflection hologram under tungsten halogen illumination, the chromatic blur will be substantial for image points far from the hologram's surface. Illuminating such a hologram with a narrow-band LED will lessen the chromatic blur.

As stated above the spectral characteristics and size of an illuminating source are of great importance to the optimization of the reconstruction of a color reflection hologram. Narrow band emission near the recording wavelengths ensures a high degree of fidelity in terms of color reproduction, increased resolution and better contrast as there are less spectrum components to contribute in scatter noise. In the case of a broadband color reflection hologram, LED illumination can assist to a better image and increased depth. Furthermore, through variable intensity mixing of the RGB LEDs beams, fine adjustment of the white point can be achieved after the recording of a color hologram. The HoloFoS-λ is the successor of the HoloFoS III hologram illuminating device; both use dichroic combiners in order to produce a coaxially mixed RGB beam. The LED head of the device is mounted on an extendable arm with three pivot joints and a novel mounting base for table or wall mount (figure 6).

Figure 6. The HoLoFoS-λ mounted on a tabletop and a close up of the LED head of the device.

The device is equipped with single-chip red, green and blue LEDs with independent precision current control for each color. In this way, the color gamut achievable by the selected LEDs can be achieved through varying the driving currents. The light emitted by each LED is collected by a small lens and steered through two dichroic combiners that mix the three beams into a coaxial exit beam. As a result, the HoLoFoS-λ hologram illuminating devices reconstruct deep single-beam color holograms with enhanced contrast and saturated colors. The dominant wavelengths of their RGB LEDs match the recording wavelengths of the ZZZyclops camera and thus provide enhanced color reconstruction. The narrow-band emissions of the LEDs (figure 7) and the small dimensions of the LEDs chips (typically 1x1 mm up to 2x2 mm) minimize the chromatic blur and the source size blur as described by equations (2) and (3). Color balance can be easily adjusted by the precise control of the LEDs driving currents.

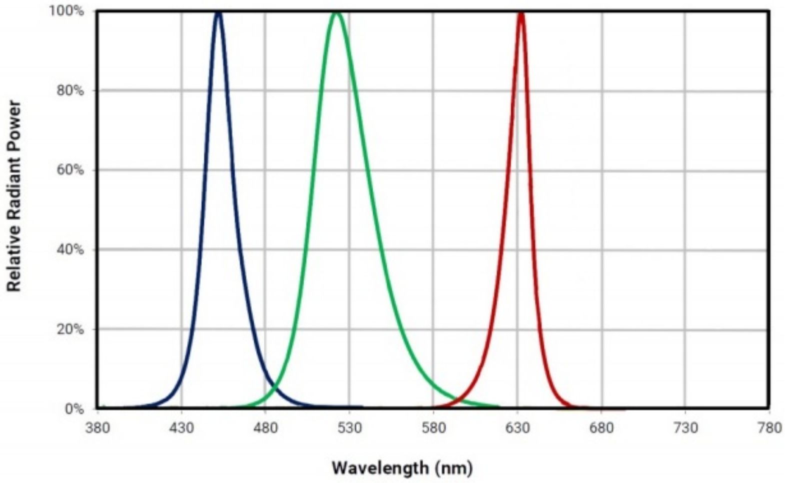

Figure 7. The HoLoFoS-λ blue, green and red LEDs' spectrum.

3. THE ZZZYCLOPS V2 CAMERA

The ZZZyclops V2 camera (figure 8) is actually an RGB laser opto-mechanical device which provides a mixed "white" exit beam for the recording of Denisyuk-type color holograms. The camera has three TEM00 DPSS single-frequency SLM lasers with wavelengths of 457nm, 532nm and 640nm and powers of 200mw,500mw and 500mw respectively. Each laser is mounted on a TEC plate to achieve a vibration free thermal management. The emitted three laser beams are combined into one "white" beam that passes through the microscope objective and the pinhole of a spatial filter assembly positioned just before exiting the camera's housing. The spatial filter provides a properly expanded and filtered RGB-illumination on the recording plate. A polarization rotator is mounted before the spatial filter capable of simultaneously rotating the polarization vectors of the three mixed beams at the same angle. The camera has 4 electromechanical shutters to block-unblock each of the 3 laser beams as well as the mixed RGB beam. These shutters independently control the exposure times of the holographic plate to each of the 3 laser wavelengths. The camera has 3 neutral density filters (ND) mounted on motor actuated rotators in order to adjust selectively the intensity of each individual beam if necessary. There are 4 temperature sensors inside the camera, three of them monitoring the "hot" TEC plates surfaces (i.e the ones in direct contact to the bases of the lasers heads) while the fourth monitors the air temperature inside the camera's housing. A fifth sensor fitted outside the camera's housing monitors the room's ambient temperature and relative humidity. A Main Control Unit (MCU) inside the camera's housing running embedded proprietary software is responsible for all control functions of the system: temperature monitoring, exposure times, ND rotation etc. A laptop computer is provided with already installed laser and TEC monitoring software as well as the ZZZyclops visual Interface; the laptop interfaces to the camera through a USB cable. The ZZZyclops Interface software provides a graphical user interface to the embedded software running in the MCU (figure 10). The Interface informs the user and allows all critical functions for the everyday use of the camera. All lasers, TECs, optical components and electromechanical components are mounted on a 45x45x2.5 cm aluminum honeycomb optical breadboard in the front compartment of the cameras' housing (figure 9) while power supplies, laser heads controllers and TEC controllers are mounted on a aluminum sheet frame in the back compartment of the cameras' housing. The honeycomb optical breadboard, characterized by a very low coefficient of thermal expansion, also in turn serves as a large-heat sink for the TEC plates. The upper part of the cameras' housing can be conveniently lifted up at any time in order to access the optical breadboard for re-aligning the beams or for spatial filter adjustments.

Figure 8. The ZZZYclops V2 camera side view.

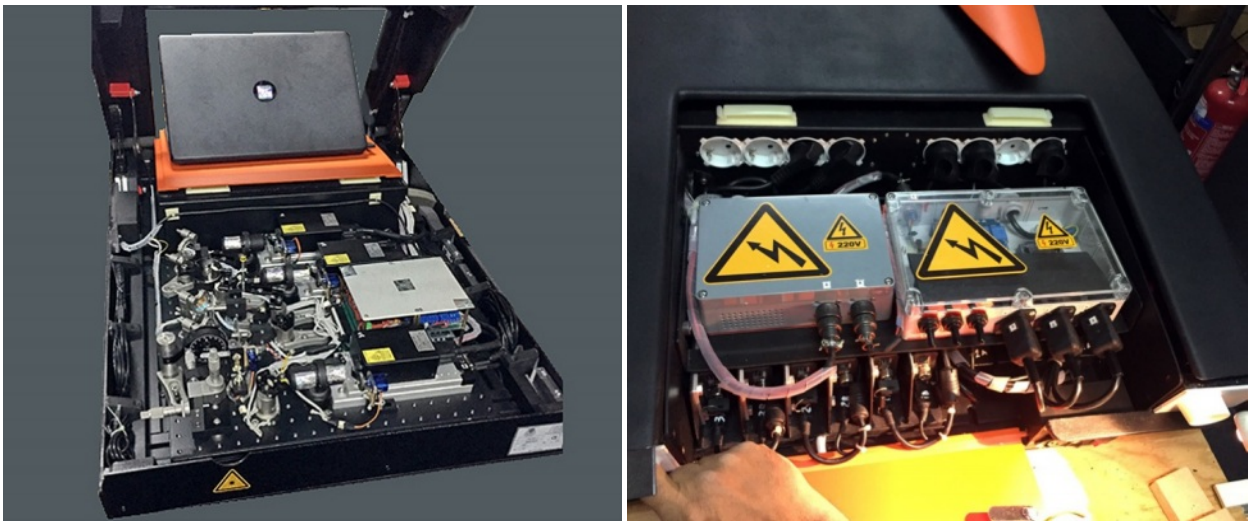

Figure 9. From left to right: front compartment with lasers and optics on honeycomb breadboard and back compartment with power supplies, lasers' and TECs controllers.

Figure 10. The ZZZYclops graphical control interface.

The camera's control software accounts for exposing the holographic plate either in a 3-beams simultaneous mode or single-beam sequentially. The main features of the V2 camera are summarized in Table 2.

Table 2. ZZZyclops V2 camera main features

Lasers
Cobolt Twist CW Single Frequency SLM DPSS 457 nm 200 mW
Cobolt Samba CW Single Frequency SLM DPSS 532 nm 500 mW
Cobolt Bolero CW Single Frequency SLM DPSS 640 nm 500 mW

Thermal management	PC graphical interface functions	Dimensions and Weight
Laser heads mounted on Cobolt TEC plates	Toggle shutters ON/OFF	64x95x25 cm, 25 Kgr
Honeycomb aluminum breadboard acts also as a massive heat sink	Set per laser different exposure times	**Ambient temperature operation**
Passive airflow	Delayed start of exposures	10-40 ^{0}C
Continuous temperature monitoring	Simultaneous or sequential exposures for Red, Green and Blue	**Ambient humidity operation**
Auto shutdown in case of overheating	Continuous monitoring of temperatures at laser heads' bottom plates, enclosure temperature, room temperature and relative humidity	0-60% RH non condensing
Optics	Neutral density filters rotation in both directions	
All optics are anti-reflection coated	Audio and visual alarms at start and end of exposure	
Tuned dichroic beam combiners		
Flat retardance over 457 to 640 nm range achromatic half-wave plate		

3.1 V2 camera versus V1 camera

The V1 camera, still in operating condition, was introduced in 2012 and reliably served its purpose as a transportable system for a number of milestone holographic recordings inside museums[3]. The main technical limitations to overcome during its development stage were imposed by the lack of availability at that time of a reliable solid state red laser with enough power for short exposures on a 30x40 cm silver-halide plate. This problem was addressed by building our own version of a TEC stabilized red-diode laser and incorporating an optical isolator and a Fabry–Pérot scanning interferometer downstream the red beam at the cost of added complexity and dimensions of the optical layout plus an increase to the total weight of the V1. The lasers fitted in the V1 camera were a 50 mW DPSS at 457 nm, a 100 mW DPSS at 532 nm and our 100 mW DL at 639nm. Ten years later the advent of more powerful, stable, single frequency DPSS lasers added degrees of freedom to the design of the ZZZyclops V2 camera resulting in a more compact layout, less optical components, reduced weight and a four to five-fold increase in optical output power. The new camera allows for short exposures, typically less than 10 seconds on a 30x40 cm U04 silver-halide plate (published sensitivity 200 $\mu J/cm^2$ per color) and less than 5 seconds on a 30x40cm U08 (published sensitivity 120 $\mu J/cm^2$ per color) or on a pre-sensitized BBPan plate (published sensitivity for both 120 $\mu J/cm^2$ per color). A series of successful experimental recordings on Bayfol XH200 at the suggested by the manufacturer energy dosages and under different modes of exposure will be reported in a future paper.

4. CONCLUSIONS

A new holography camera has been developed and produced for the ZZZyclops system of mobile equipment for the in-situ production of OptoClones of valuable artworks inside museums. The new ZZZyclops V2 camera is part of the ZZZyclops V2 system which also includes the new depth adjustable object-plate boxes, our standard lightproof tent chamber and the two-tier passive isolation platform for the object-plate space.The new V2 camera is the successor to the ZZZyclops V1 with a four to five-fold increase in optical output power, a reduced footprint and added functionality to the controlling software. The increased output power of the fitted lasers permits to record high-quality color holograms of large dimensions in silver halide materials in short exposure times but also due to the proved stability of our setup succesfull recordings on photopolymer materials with longer exposures. OptoClones™ is a worldwide registered trademark of the Hellenic Institute of Holography.

AKNOWLEDGEMENT

The 3D-design visual concept of the ZZZyclops V2 laser camera as well as its subsequent successful interpretation into a fully-functional commercial product would have been practically impossible without the talent and full commitment of the itnernationallly awarded industrial-designer Yiannis GEORGARAS, a long-standing partner of the Hellenic Institute of Holography. Regrettably, Yiannis GEORGARAS passed away only weeks prior to the publication of this article, in memory of whom the authors wish to dedicate it. We expect his brilliant output in terms of practical and functional technical solutions to survive his memory as one of the many unsung contributors in display holography. .

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TRACK 3.

Electronic, Digital and Computer-Generated Holography

Real-time 4K image holographic video display for real object

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ABSTRACT

The proposed system can capture 3D point cloud data of a real object and generate 4K full color image hologram at 30 frames per second. The real object is captured by Intel RealSense which has RGB camera and two infra-red cameras to capture depth image with stereoscopic measurement. Captured color image and depth image are integrated to create point cloud data that have 3D coordinates with color information. The point cloud data are stored in a temporal file and image hologram calculation program loads the data and generates holographic fringes. In optical reconstruction experiment, a human face is captured and generated hologram is displayed on a 4K LCOS illuminated by green laser and real-time motion has been observed.

Keywords: computer-generated hologram, real object, holographic video, three-dimensional display, real-time holography

1. INTRODUCTION

We have been studying real-time generation of full color image hologram.[1–3] Recently, interactive full color 4K (3,840 × 2,160 pixel) image hologram is realized.[2] The viewer can manipulate 3D object in Unity game engine and 3D point cloud data is send to a hologram generation software. In this research, a depth camera is used to capture a real object and converted point cloud is used for hologram generation. It is realized that real-time capture, convert, hologram generation and display at about 20 frames per second with a personal computer with 10th generation of Intel Core-i9 processor.

2. CAPTURING REAL SCENE WITH DEPTH CAMERA

2.1 Capturing point cloud with texture

Intel RealSense D435 device[4] is used as a depth camera. The device has one RGB camera, one infrared projector and two infrared cameras located left and right of the projector for stereoscopic measurement of the depth. The RGB resolution is 1,920 × 1,080 pixel and field of view is 69° × 42°. The depth resolution is 1,280 × 720 pixel, field of view is 87° × 58° and ideal range is .3 m to 3 m. The device also has a vision processor board and USB-C
3.1 interface.

2.2 Writing point cloud data for hologram calculation

Point cloud is easily captured with a sample program "PointCloud" included in RealSense SDK 2.0.[5] The C++ code is modified to output point cloud data file for full color 4K image hologram calulation. Major modifications are listed below.

1. Integrate RGB image and depth image to obtain 3D point coordinates and color information.
2. Crop the central part of the image if necessary.
3. Remove background to decrease number of points for fast calculation.
4. Save point cloud to a binary file for hologram calculation.
5. Create a dummy file as 'ready' signal for hologram calculation program .

Then, image hologram is calculated from the saved binary point cloud as same mannar of the previous reports.[2, 3]

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Figure 1. Captured image by 'point cloud' program.

Figure 2. Perspective image of converted point cloud.

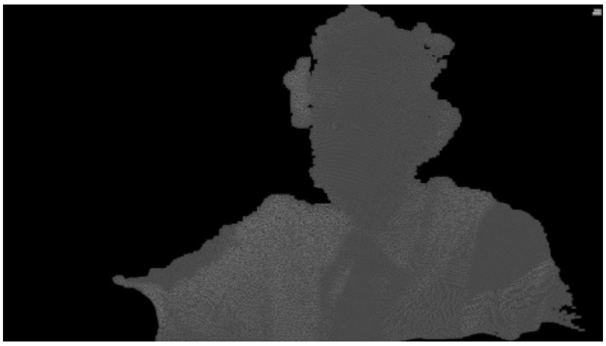

Figure 3. Calculated 4K full color image hologram.

Figure 4. Numerical reconstruction of green component.

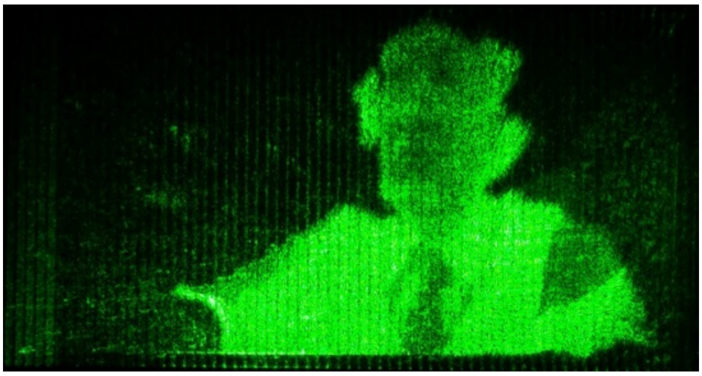

Figure 5. Optically reconstructed image of greencomponet by 4K LCOS.

3. RESULTS

All processing time are measured on a personal computer whose specs are CPU: Intel Core i9-10900KF 3.7GHz, OS: Windows 11, Compiler: Visual C++ 2019.

3.1 Capture and conversion

Figure 1 illustrates a perspective image of point cloud captured by the original "PointCloud" program. Figure 2 shows a perspective image converted to hologram calculation data by modified capture program. Note that Fig. 1 and Fig. 2 are captured in different date and the converted data of Fig. 2 are used for hologram calculation. The data consist of 34,472 points and each point has position (x, y, z), amplitudes for red, green and blue components.

3.2 Hologram calculation and reconstruction

Calculation method is same as the interactive hologram generation.[2, 3] Figure 3 shows 4K full color image hologram fringe generated from point cloud shown in Fig. 2 Three holographic fringes for red ($\lambda = 633$ nm), green ($\lambda = 532$ nm) and blue ($\lambda = 473$ nm) are calculated separately and superposed in a single image. Since the fringe is image hologram, the shape is similar to the captured object. Numerical reconstruction in Fig. 4 is obtained by the simulation software for rainbow hologram.[6] Since the simulation software can handle single fringe only, green component is simulated and texture can be recognized. Optical reconstruction of green component is shown in Fig. 5. The hologram is displayed on 4K LCOS (pixel pitch: 4 μm) and illuminated by a green laser. Although the quality is not as good as the simulation shown in Fig. 4, similar image is observed. Typical cycle time from capture to display is 50 ms, while hologram part is 41 ms.

4. CONCLUSION

It is realized that real time capture, conversion, calculation and display of full color 4K image hologram of real object in about 20 frames per second. Although the cycle time is good enough for a practical use, reconstructed image quality must be improved. Full color reconstruction will be the future work.

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Twin noise reduction of spatial light modulator with correction of phase modulation error

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ABSTRACT

In this paper, the twin noise reduction algorithm that accounts for the phase modulation error is presented and it is able to significantly reduce twin noise and improve the quality of holographic images. A reflection-type liquid crystal display (HX7322) with full high-definition resolution is used as a phase-only spatial light modulator (SLM). The phase modulation characteristics of the SLM are measured using a Mach-Zehnder interferometer. We conduct numerical simulation using an algorithm to compensate for the modulation errors of the object wave based on the measurement results. We analyzed the correlation between wavefront modulation errors and the occurrence of twin noise.

Keywords: Digital holography, Spatial light modulator, Holographic display, Phase modulation, Twin noise reduction, Liquid crystal, Interferometer, Modulation error

1. INTRODUCTION

Digital holography is a technique for recording and reproducing both the phase and amplitude of object wave [1]. Complex spatial light modulator (SLM) is a crucial component of holographic display since the SLM enables the reproduction of the wavefront of the object beam by modulating both its amplitude and phase [2, 3]. However, most SLMs used in holographic displays are restricted to modulating either the phase or amplitude of light [4]. The amplitude-only SLMs are susceptible to DC and twin noise when reproducing object waves [5]. So, eliminating twin noise is essential to obtaining high-quality holographic images. Various methods have been proposed, such as using the observer's pupil as an optical filter in off-axis holograms [6] or a frequency filter in 4f system [7].

The phase-only SLMs are expected to have the advantage of reproducing object waves without DC and twin noise. But twin noise usually appears even with phase-only SLMs due to the error in phase modulation. In this paper, we present a twin noise reduction algorithm that accounts for the phase modulation error and are able to significantly reduce twin noise and improve the quality of holographic images. A reflection-type liquid crystal display (HX7322) with full high definition resolution is used as a phase-only SLM. The phase modulation characteristics of the SLM are measured using a Mach-Zehnder interferometer. We conducted numerical simulation using an algorithm to compensate for the modulation errors of the object wave based on the measurement results. We analyzed the correlation between wavefront modulation errors and the occurrence of twin noise.

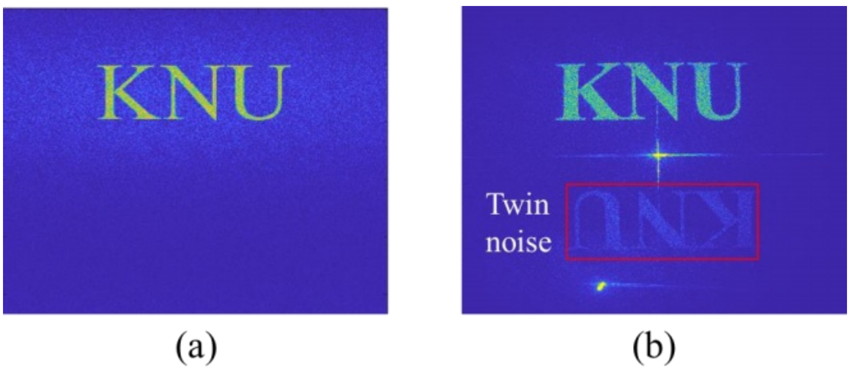

Figure 1. (a) Simulation and (b) experimental measurement from phase-only Fourier hologram.

2. NONLINEARITY OF PHASE MODULATION

The generation of twin noise in the reproduction of an image through a phase-only SLM is assumed to occur due to the inherent limitation in achieving precise modulation with the optimal phase shift value. In order to examine the influence of phase modulation errors on the generation of twin noise, supplementary simulation is performed. The simulation is based on an ideal situation, where the absence of twin noise was observed during linear modulation of the image using a phase-only SLM with an 8-bit coding depth. To analyze the effects of non-linear phase modulation, the reproduced image is obtained by applying a gamma value to induce non-linear phase modulation. From the simulation, it becomes obvious that the magnitude of twin noise generation increases proportionally with larger absolute values of the gamma parameter. Based on there facts, an experimental setup is developed to quantify modulation errors in real-world situation [8]. Figure 2 depicts a Mach-Zehnder interferometer, capable of capturing interference patterns using an image sensor.

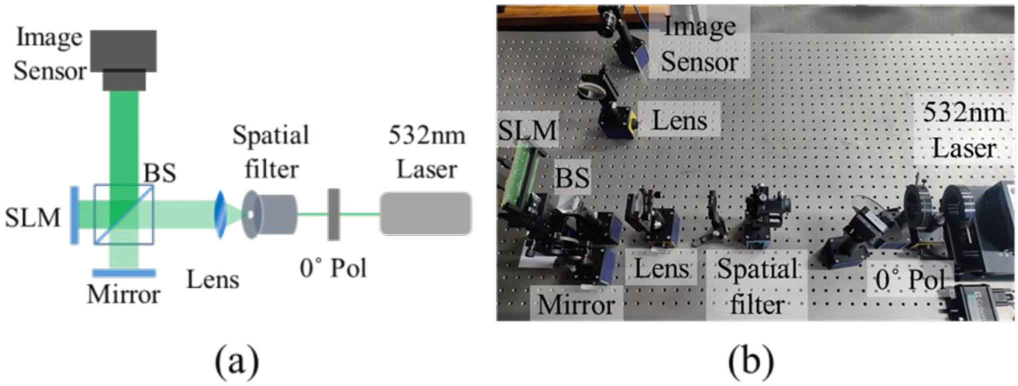

Figure 2. (a) Schematic and (b) experimental setup for measuring interference pattern according to the phase shift.

To assess the phase shift values, the liquid crystal on silicon (LCoS) microdisplay as the phase-only spatial light modulator (SLM) is divided into two halves. A zero phase is generated at the top half to reproduce the interference pattern with the reference phase. The phase shift at the bottom half is measured by progressively increasing the gray level, and the phase modulation value is evaluated. The interference patterns captured using the proposed optical system are depicted in Figures 3(a-c), while Figure 3(d) illustrates the resulting graph of calculated phase modulation values. A notable discrepancy is observed when comparing it to the linear modulation, indicating a significant error. In order to compensate for this error, the gamma value of nonlinear modulation is tuned based on the data, and the computer-generated hologram (CGH) is encoded in the SLM.

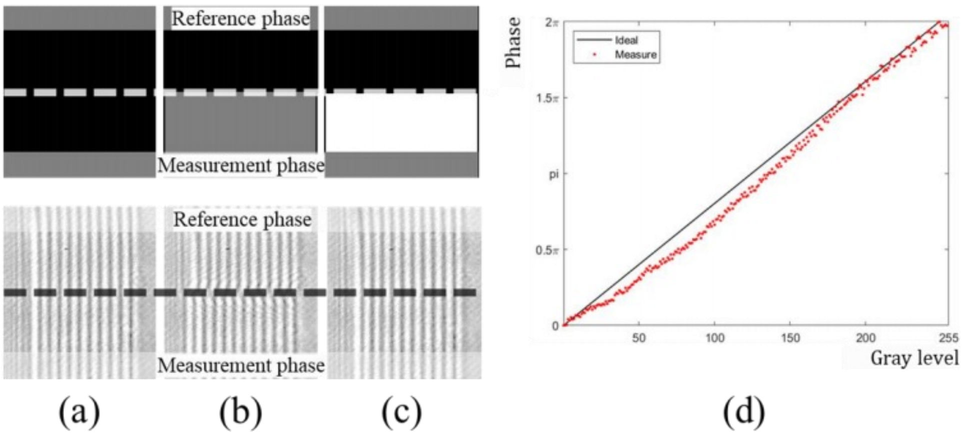

Figure 3. Experimental result captured using the proposed optical system (a) 0, (b) π, (c) 2π, and (d) graph depicting the phase modulation characteristics.

3. RESPONSE TIME OF LIQUID CRYSTAL

Although the significant reduction in twin noise is achieved through the gamma-tuning of the CGH, a small amount of twin noise still remains in the reproduced image. To further improve this issue, an experiment is carefully conducted to find other causes of phase modulation error. It is identified that the overestimated response time of the liquid crystal (LC) during the light source scanning in the optical system results in a significant problem. Experimental results show that errors occur when the light source is tuned on within the LC response time [9]. The SLM maintaines a stable phase shift value approximately 30 ms delay from the initiation of the channel signal, remaining unaffected by the LC's rising time. Accordingly, a shutter circuit is developed to limit the turn-on time of light source to only 9 μs after 30 ms delay from the rising edge. Figure 4(a) shows the configuration of the shutter circuit that achieves synchronization between the laser light source and the SLM so that the light source is turned on only in the proper LC state. Figure 4(b) depicts the LC state corresponding to the SLM's green channel signal, and the red pulse wave indicates the period during which the light source is scanned.

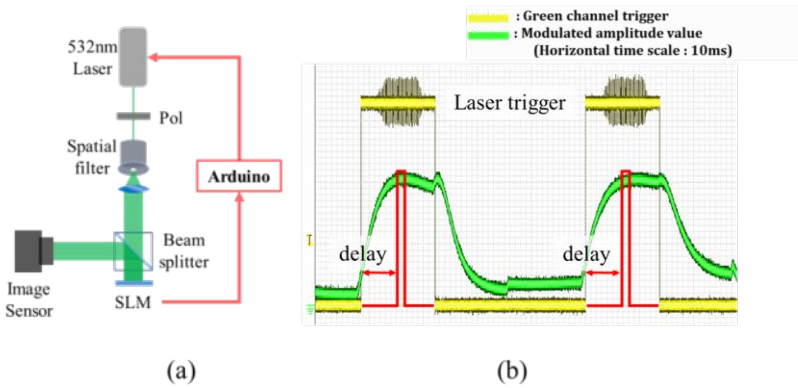

Figure 4. (a) Schematic of the proposed shutter circuit, and (b) a time-diagram where the light source is turned on only during the narrow interval after some delay according to the signal of SLM.

4. CONCLUSION

Experimental results shown in Fig. 5 present Fourier holograms captured on three different cases. Figure 5(a) represents the result of the optical system under initial conditions, yielding an SNR of 10.39 dB. Figure 5(b) shows the result obtained by applying the proposed CGH, while Figure 5(c) exhibits the outcome of applying the CGH in conjunction with the shutter circuit. The application of the CGH resulted in a 1.5 times reduction in twin noise compared to the initial condition, and the additional implementation of the shutter circuit led to a 2.4 times reduction. These results validate the experimental effectiveness of the proposed method in reducing twin noise.

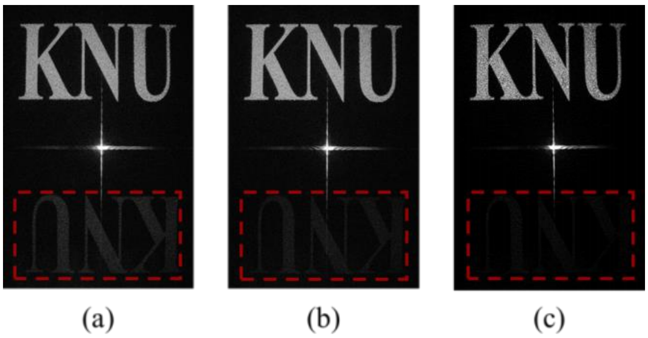

Figure 5. Experimental result: Fourier Hologram (a) of initial condition (SNR: 10.39 dB), (b) applying the improved CGH (SNR: 16.49 dB), and (c) applying the improved CGH with the proposed shutter circuit (SNR: 24.62 dB).

ACKNOWLEDGEMENT

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Super resolution image generation from the complex field information generated using deep learning model

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ABSTRACT

Super-resolution hologram generation via deep learning models has become an area of significant research in the field of optics and computer vision. The primary objective is to improve the holographic reconstruction image quality using the deep learning models for the optical configuration of 4-step phase-shifting digital holograms acquired numerically considering the polarized based CCDs. In this paper, we propose a model to extract the objects complex field information at the hologram plane from four predicted high resolution phase shifted interference patterns and then propagate it to the desired object plane for image reconstruction suppressing the DC and conjugate noise. The simulation results show that the proposed network can predict four high resolution interference patterns from its counterpart lower resolution interference patterns when the network is trained on only one pair of high and low resolution phase shifted interference pattern instead of all four pairs.

Keywords: Phase-shifting holography, computer generated hologram, super-resolution, deep learning holography

1. INTRODUCTION

Digital holography has emerged as a powerful and versatile technique for capturing and reconstructing three-dimensional (3D) images with remarkable realism. Unlike traditional photography, which records only the intensity of light, digital holography enables the capture and storage of both the amplitude and phase information of a wavefront. The fundamental principle behind digital holography lies in the interference of light waves. When an object is illuminated with a coherent light source, the light waves interact with the object, resulting in complex interference patterns. These interference patterns, known as holograms, carry a wealth of information about the object's shape, depth, and texture[1]. However, these interference patterns carry DC and the conjugate components as well which hinders the reconstruction of the object information. To suppress these terms, off-axis or phase shifting holography are frequently used [2]. The phase shifting requires multiple capturing of the holograms, making it sensitive to the system vibrations. Moreover, conventional holography suffers from limitations in spatial resolution due to factors such as the pixel size of the recording sensor or the wavelength of the illuminating light.

Recently, deep learning technology is emerging in a wide variety of scientific fields [3]. In the context of digital holography, deep learning based super-resolution techniques have the potential to push the boundaries of holographic imaging, enabling high quality reconstruction. Super-resolution holography seeks to overcome the traditional limitations in digital holography by utilizing advanced computational algorithms and deep learning techniques to enhance the resolution and details of reconstructed holograms. By training deep neural networks on a diverse set of high-resolution holograms and their corresponding low-resolution counterparts, these networks learn to capture and restore fine details that were previously beyond the reach of conventional holography[4-6].

In this paper, we present a deep learning based super resolution image reconstruction at object plane from the complex field extracted at the hologram plane [7]. The complex field extraction in the hologram plane has higher similarity to the interference pattern in the same plane than the complex field in the object plane. This higher similarity usually gives higher complex field extraction quality to the proposed approach. The complex field is extracted from four predicted high resolution phase-shifted interference patterns as we are considering the optical geometric configuration of 4-step phase-shifting digital interferometric holograms acquired through the polarized based CCDs. Note that in the proposed approach, the model is trained on only one pair of low and high resolution of interference patterns in the given dataset. The trained

model is then used to predict all four high resolution phase-shifted interference patterns from their respective low resolution phase shifted interference patterns.
We validate our approach using dataset generated by numerical simulations of 4-phase shifting digital holography. The simulation results show that we can reconstruct higher quality image at certain depth with the extracted complex field information from 4-phase shifted interference patterns predicted by the proposed model.

2. METHODOLOGY

We adopt a four step phase-shifted holography technique to numerically calculate the complex field information considering the subpixel structure of the polarized based CCD as shown in Fig. 1. The combined reference and object beams at the hologram plane after numerically propagating using the angular spectrum method are captured by a polarized image sensor. Each pixel of the polarized image sensor consists of 4 sub-pixels which have linear micro polarizers of 0°, 45°, 90°, and 135°, shown in gray, yellow, green, and blue boxes in figure below, respectively. The linear micro polarizers in the sub-pixels give different phase delays to the reference and object beams, enabling the 4-phase-shifting digital hologram.

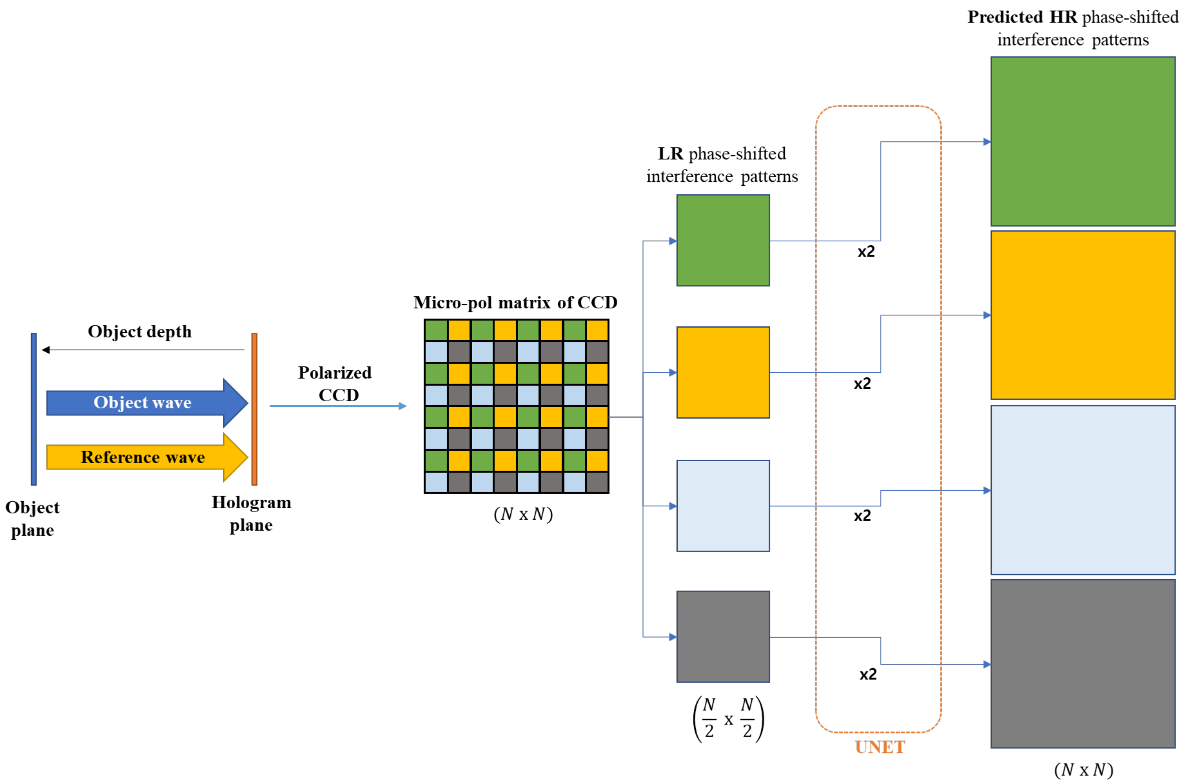

Figure 1. Setup configuration for high resolution 4-phase shifted interference holograms predicted by UNET from the corresponding low resolution 4-phase shifted interference holograms.

The raw data on the hologram plane is then separated according to the polarizer directions of the sub-pixel. The resulting 4 low resolution interference patterns, i.e., $LRI_{0^\circ}, LRI_{45^\circ}, LRI_{90^\circ}$ *and* LRI_{135° respectively correspond to 0, π/2, π and 3π/2 phase shift between the reference and object beam. These low resolution interference patterns are then used as an input to the trained model to predict high resolution phase-shifted interference patterns, $PHRI_{0^\circ}$, $PHRI_{45^\circ}, PHRI_{90^\circ}$ *and* $PHRI_{135^\circ}$ respectively.

The object complex field U extracted at the hologram plane is then obtained by,

$$U = \left(PHRI_{0^\circ} - PHRI_{90^\circ}\right) + i(PHRI_{45^\circ} - PHRI_{135^\circ})$$

In the proposed method, MNIST dataset is used that contains 5000 training and 5000 validation images of 0 to 9 digits. The hologram plane or polarized CCD pixel pitch is 10um, object distance is 16mm and wavelength is 532nm. The input image size to the UNET model is 128 x 128 pixels. From the raw data on the hologram plane, four high resolution interference patterns $HRI_{0^\circ}, HRI_{45^\circ}, HRI_{90^\circ}$ and HRI_{135° respectively with phase shifts of π/2 between them and the corresponding complex field information with pixel size of 128 x 128 (N x N) are calculated as ground truth. Four low resolution interference patterns of size 64 x 64 (N/2 x N/2) are obtained from corresponding high resolution patterns by simple decimation and then interpolated to size of 128 x 128 (N x N). The network is trained to output ground truth high resolution interference pattern HRI_{0° from LRI_{0°. The network is trained for single pairs of low and high resolution interference patterns and is used to predict all four interference patterns. A single pixel shift is considered to account for the phase shift while calculating the low resolution interference patterns from the ground truth high resolution interference patterns. Figure 2 shows the single training pair of low and ground truth high resolution interference patterns at the hologram plane.

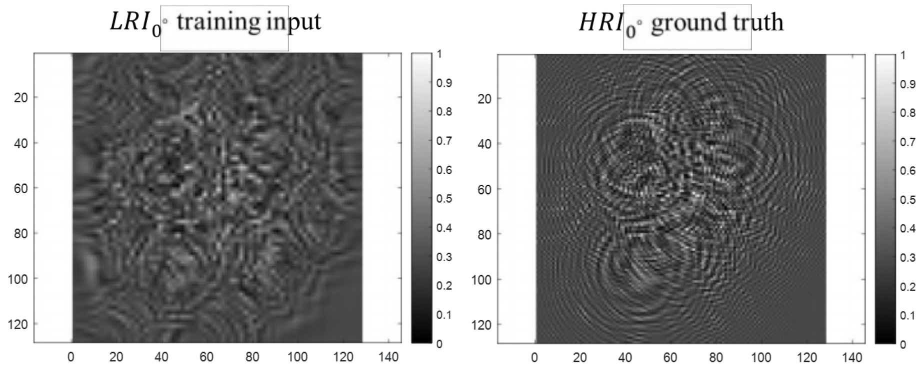

Figure 2. Single pair of low and ground truth interference patterns used in model training.

3. NETWORK ARCHITECTURE

In the proposed method, we have used the UNET architecture and regression layer for enhancing the resolution and details of low resolution images. Figure 3 shows the UNET architecture used in our MATLAB implementation. The UNET architecture [8] consists of the encoder path responsible for capturing low-level and high-level features from the input low-resolution interference pattern. It progressively down-samples the image, extracting hierarchical representations through convolutional and pooling layers. The decoder path then performs the upsampling and reconstruction, generating a high-resolution interference pattern. The skip connections between corresponding encoder and decoder layers allow for the fusion of low-level and high-level features, facilitating the recovery of fine details during the reconstruction process.

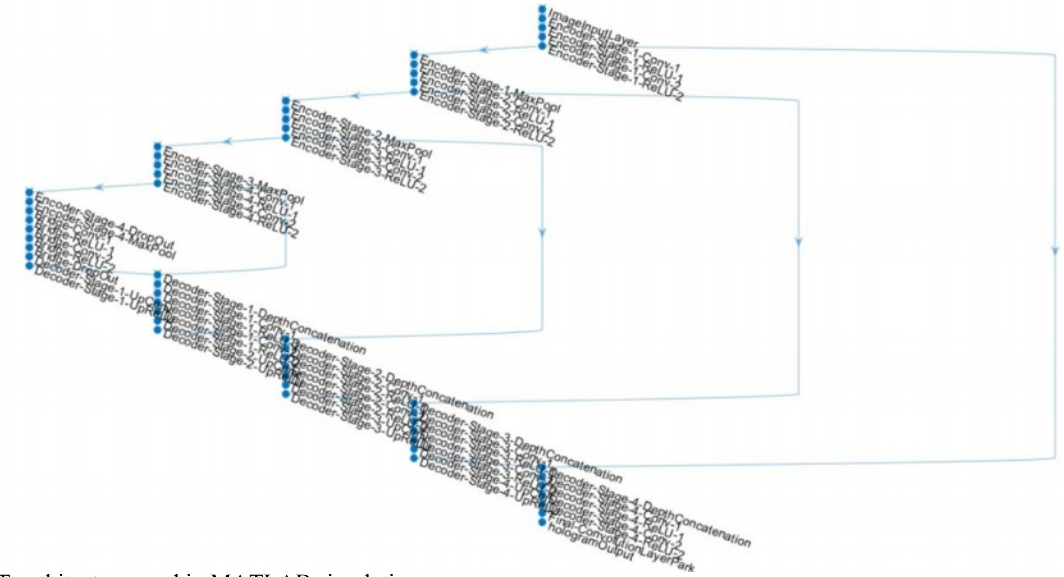

Figure 3. UNET architecture used in MATLAB simulation.

To train the UNET for super-resolution, a regression-based loss function is used. A pixel-wise comparison between the predicted high-resolution interference pattern and the corresponding ground truth is enabled. Common loss functions for UNET image regression in super-resolution include mean squared error (MSE) or perceptual loss, which leverages pre-trained deep neural networks, such as VGG or ResNet, to capture perceptual similarity between the predicted and ground truth images. However, in the proposed method only MSE is considered in optimization process through the Adam optimizer.

4. TRAINING RESULTS

For the validation of the proposed method and network architecture, we first train and test the network using the simulation data generated by the numerical propagation as shown in fig. 1. In the simulation, objects in the MNIST dataset are propagated to a fixed distance of 16mm from the object plane to the hologram plane via angular spectrum method used in [9]. The complex information is then used to obtain 4-phase shifted ground truth interference patterns as shown in last row of fig.4. The low resolution interference patterns are then calculated from the corresponding ground truth high resolution interference patterns after first being decimated to N/2 x N/2 and then interpolated back to N x N resolution as seen in first row of Fig. 4. The model is trained on the single pair of low and ground truth interference patterns ($LRI_{0^\circ}$and HRI_{0°) for all objects in the MNIST dataset. The training is done with batch size of 30 and for 50 epochs. Once the model is trained, all 4 low resolution interference patterns are inputted to the same UNET model to generate 4 predicted high resolution interference patterns as seen in the middle row of Fig. 4. From figure 4 and figure 5, we can see that the model predicts the interference patterns and complex field amplitudes and phases with much better quality when compared with the corresponding low resolution interference patterns and complex field amplitude and phase information's, respectively.

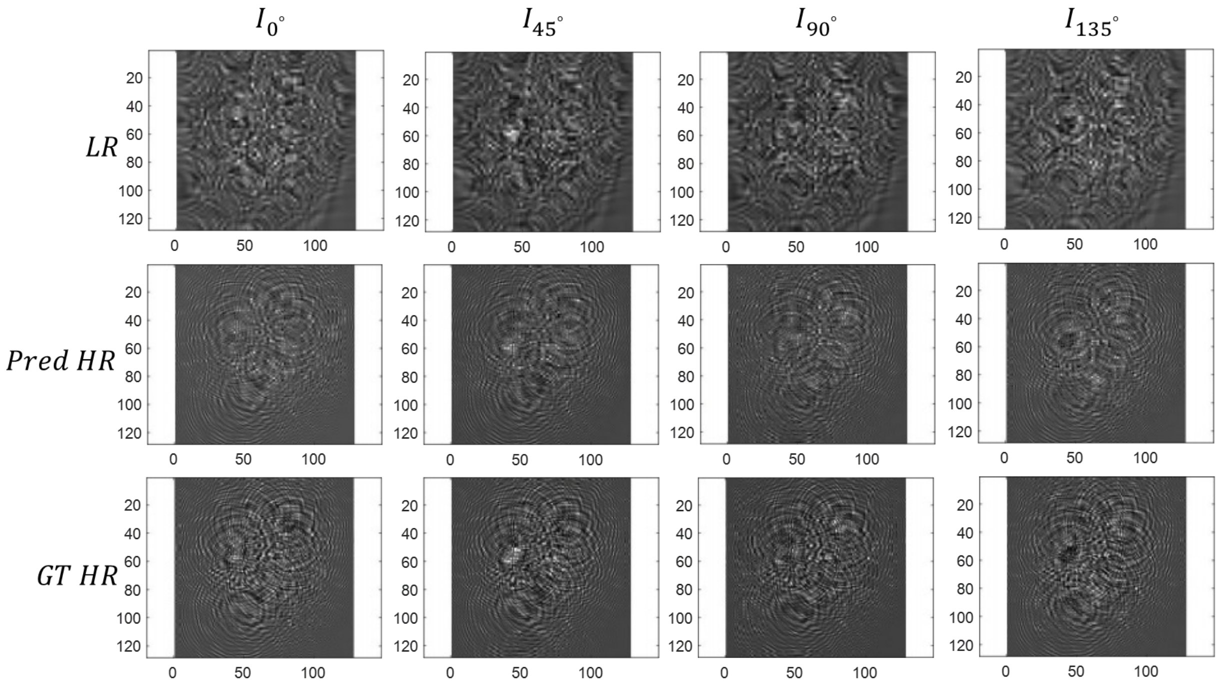

Figure 4. The first row shows the low resolution 4 phase shifted interference patterns and its corresponding ground truth high resolution interference patterns in the last row. The middle row shows the predicted high resolution interference patterns for single pair trained ($LRI_{0^\circ}$and HRI_{0°) in the UNET architecture.

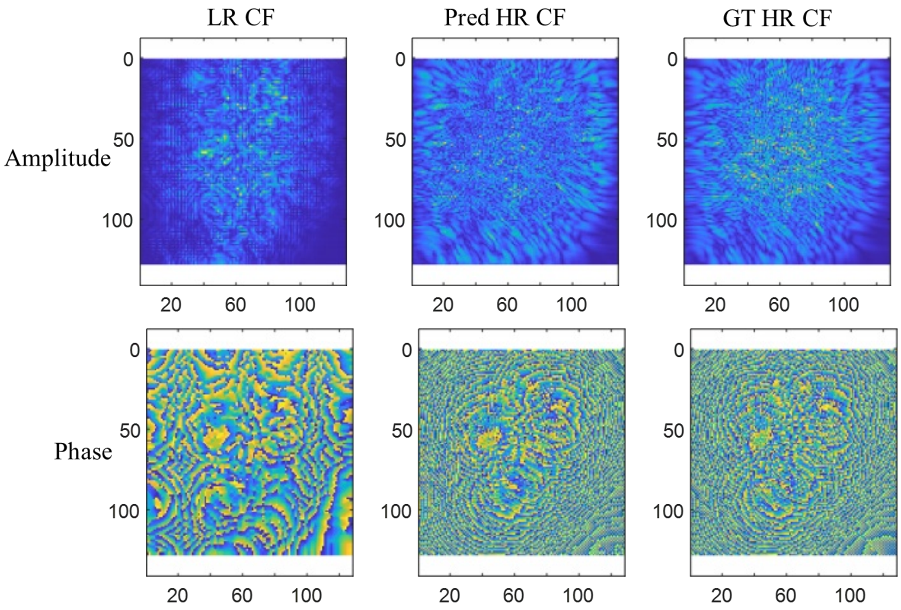

Figure 5. It shows the amplitude and phase information for the extracted complex field information from the 4 phase shifted interference patterns for low, predicted, and high resolution respectively.

Figure 6 shows the numerically reconstructed result from the propagated object complex field information back to the object plane. The object complex field information is calculated from the 4 predicted high resolution phase-shifted interference patterns by the trained network. We can see from the figure that network prediction is much better than the low resolution hologram reconstruction. From figure 7, we can see that network predicts complex field information for different object distances for the originally trained UNET model at 16mm object depth. However, the best reconstruction quality is achieved at the original 16mm depth.

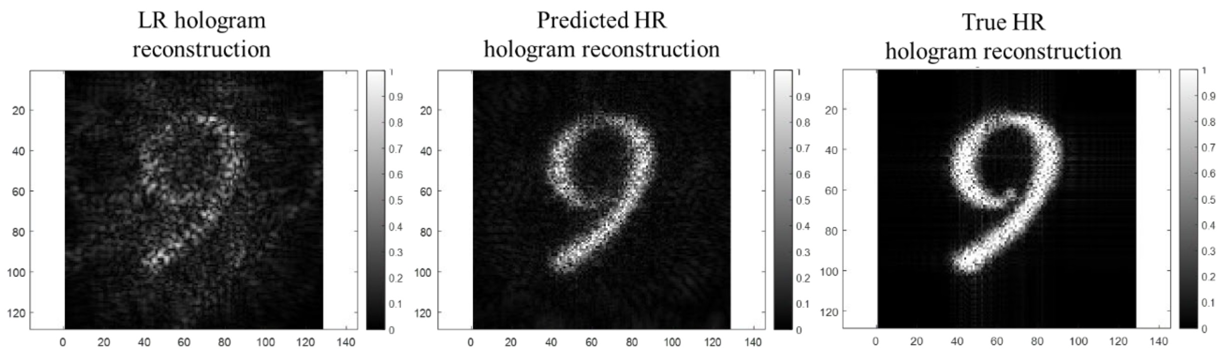

Figure 6. The reconstructed object complex field information at the object plane for the low resolution, predicted high resolution and the ground truth high resolution complex fields respectively.

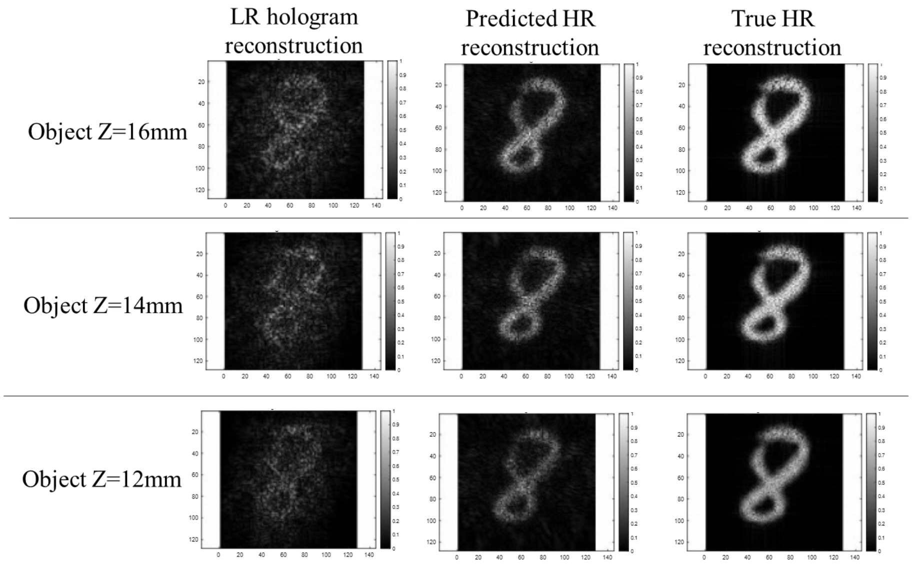

Figure 7. It demonstrates the network capability of predicting complex information for image reconstruction at different depths (14mm and 12mm) than the original trained depth (16mm) information.

5. CONCLUSION

In this paper, we proposed a learning-based complex field extraction from the predicted 4-phase shifted high resolution interference patterns at the hologram plane directly. The complex field is then back propagated to the object plane for super resolution image reconstruction. The final reconstruction is free from DC and conjugate components. The proposed technique was demonstrated by simulations carried out on the MNIST dataset. The single pair of low and high resolution interference patterns at the hologram plane for all objects in the MNIST dataset are used in training the UNET architecture. The single pair trained UNET is then used to predict all four phase shifted high resolution interference patterns. The simulations show the validity of the proposed network and methodology.

ACKNOWLEDGEMENT

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EcHoLas: A compact direct-write digital holography printer

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ABSTRACT

EcHoLas is a European funded project targeting the development of a fast desk-top digital holographic printer capable of producing full-colour wide-angle-of-view direct-write holograms with a hogel size of 250 microns on A4 photopolymer. The principal challenges involve the design and fabrication of a highly sophisticated compact light engine, red, green and blue semiconductor lasers and a precision stage capable of low-vibration step-and-repeat operation at high speed. The developed optical engine will be described in detail and initial results of system integration will be presented.

Keywords: holographic printer, full-colour hologram, digital hologram, DWDH, direct-write holography, 1-step digital holography, desktop holo-printer.

1. INTRODUCTION

The technique of writing digital reflection holograms as a matrix of small adjacent elemental holograms (now known as 'hogels') was first demonstrated by Yamaguchi et al[1] (JP) in 1988. These early experiments, although monochromatic, slow, and employing contact apertures, led the way to the development of what is today known as DWDH or Direct-Write Digital Holography. In the late 90's Klug et al[2] (USA) working at Zebra Imaging Inc substantially improved DWDH allowing the production of large-format high-quality full-colour reflection holograms. Also, in the late 90's Brotherton-Ratcliffe et al[3] (LT) working at Geola UAB showed how DWDH could use an RGB nanosecond pulsed laser rather than the R, G and B CW lasers conventionally used. This significantly increased the print-speed and allowed high quality full-colour poster-size holograms to be produced within hours rather than days. Geola initially span out its technology to the Canadian company, XYZ Imaging Inc which was subsequently purchased by RabbitHoles Inc in 2005/6. Over the following two decades several new scientific groups and individuals[4,5,6,7,8] worked on and developed DWDH[9]. With the closure of Zebra Imaging Inc, existing commercial print-houses where clients can print DWDH holograms are extremely limited; the most notable are Geola Digital UAB in Vilnius, Lithuania and Yves and Phillipe Gentet in Seoul, S.Korea.

2. MARKET AND MATERIALS

Even though the current market for DWDH printers and prints is small, potential applications for a desktop DWDH printer are quite large. This is because the current state of DWDH technology appears to be below the threshold required in various respects. As such, today only a handful of companies offer commercial holographic printers or a printing service. And these printers and services are both expensive.

A further reason why the current market is small is the poor availability of printing material. Generally speaking, there are three types of material which can be used in a DWDH holographic printer. These are ultra-fine grain silver halide, photopolymer and photoresist. Of these only silver halide and photopolymer are suitable to produce full-colour reflection holograms. And of these, only the photopolymer material is currently freely available from what can be regarded as an acceptably reliable and stable long-term source.

But current DWDH technology significantly favours silver halide. This is because this material is naturally sensitive to nanosecond laser radiation and its energetic sensitivity is more than an order of magnitude better than that of photopolymer. As a result DWDH solutions are today essentially based on silver halide. But with the war in Ukraine having isolated the largest Russian producers, only a handful of companies can today produce the required emulsion.

The adoption of photopolymer by DWDH must therefore play a major role towards any solution to a larger market. Nevertheless, the current commercially available varieties of photopolymer are poorly sensitive to single pulses of nanosecond laser radiation. Here the diffraction efficiency obtained under nanosecond illumination simply does not translate into acceptable brightness levels (and brightness is of course highly demanded for commercial prints). In addition the very low energetic sensitivity of photopolymer precludes the use of readily available CW laser sources given that fast printing is essential.

3. FAST PRINTING WITH DWDH

3.1 DWDH Printers

A DWDH printer uses a laser and a lens system to focus laser light onto a photosensitive material to create the hogel or holographic pixel. Essentially laser light is brought to bear from both sides of the photo-material – a reference and an object beam – and the interference of these two beams at a given point produces an elemental hologram, typically square and of a diameter of around 0.25mm. Information is encoded onto this hogel by arranging for the object beam to pass through a spatial light modulator (SLM) on which digital information is displayed. Using a 2-axis translation stage, the photo-material is then advanced in sync with a laser and the updating of digital SLM data so that the surface of the required hologram is eventually covered by a matrix of abutting hogels.

3.2 Writing the Hogel - Step and Repeat

A DWDH hologram of 200mm x 300mm (approximately A4) requires 960,000 0.25mm hogels. For a desktop printer to be useful, clearly this A4 hologram needs to be printable in hours as opposed to days. However, each hogel is a hologram and the photo-sensitive material must therefore stay still during the exposure time to within better than $1/10^{th}$ of the wavelength of light – or approximately 40nm. We have two choices then. We can either "step and repeat" or we can use a translating stage operating at a constant velocity. If we step and repeat, clearly we need to accelerate and decelerate either the optical system or the photo-material extremely rapidly. However, such acceleration and deceleration will induce vibration into the system which will then require some time to dissipate. Early solutions using 'step and repeat' therefore tended to operate at less than 1Hz; this translates into a write time of >11 days.

3.3 Writing the Hogel - Constant Velocity

The alternative to 'step and repeat' is to move the stage at constant velocity. In this case the criterion of the photo-material not moving more than 40nm during an hogel exposure leads to a condition on the hogel exposure time. More specifically if we require that hogels are written at a rate of R hogels per second, then the stage speed for a 0.25mm hogel will have to be chosen to be v=0.25R mm/s. If we consider an individual exposure time, t for a single hogel, then the distance that the photo-material moves with respect to the optics within this time period is

$$d = vt = 0.25Rt \tag{1}$$

Now since we know that d must be less than 40nm, it is easy to see that the constraint on the individual hogel exposure time is that it must be smaller than 160/R microseconds. So, for example, if we were to choose a write rate of 30 hogels per second, then we would need to ensure that our exposure time was less than around 5 microseconds.

3.4 Using Nanosecond Pulsed Lasers

We can now understand why pulsed lasers, having a typical pulse duration of 50ns, have been so extensively used in DWDH. Current commercial printers built by Geola and employing modern DPSS 50ns pulsed RGB lasers operate at R=100Hz giving a write-time for our A4 example hologram of just over 2 hours 30 minutes. Certainly a lot better than the early step and repeat times of 11 days. However, with this type of laser and with fast liquid crystal on silicon (LCOS) displays (or even ferro-electric displays), one can potentially imagine attaining values of even R>200. The huge problem of course is that current photopolymers, due to the relatively slow diffusion nature inherent to the process of photo-polymerization[10,11] are simply lacking sensitivity to single pulses having a pulse duration of tens of nanoseconds!

3.5 Using Shuttered CW Lasers

Another solution is to use a shutter system and a CW laser. Acousto-optic or electro-optic systems are quite capable of very controllably chopping CW laser beams down to microsecond pulses. In addition semi-conductor lasers can be "TTL" driven to produce such pulses. So what about simply shuttering a CW laser down to 5 microseconds and using only a tiny fraction of the available power? If we do this we will arrive at another condition, this time governing the power requirement of our CW laser.

To investigate this solution we first need to get an idea of how much energy our chosen photo-material requires to adequately expose an individual hogel. Let’s go with a hogel size of 0.25mm as above and use the published energetic sensitivity of the HX200 photopolymer of 0.2mJ/mm^2 per colour. We will therefore need an energy for each hogel of 0.2/16=0.0125mJ. However, here we need to consider that the optical system of a DWDH printer is not 100% efficient. In fact, the efficiency can often be as low as 10%. Hence realistically we will need an energy per hogel of around 0.125mJ.

If we now take the case of R=30 - which implies an exposure time of 5 microseconds – we see that the laser power (for each of the three component colours) must be greater than

$$P = \frac{0.125.10^{-3}}{5.10^{-6}} = 25W \qquad (2)$$

It is possible to increase the printer optical efficiency using a variety of more complex optical solutions to around 50%. But this only reduces the required laser power to 5W. Whilst possible to achieve, clearly a printer based on such technology will be extremely expensive. Practically then, the only solution is either to use a more sensitive material or to reduce the value of R. This means that the continuous velocity stage solution can indeed work with silver halide at a reasonable hogel write rate, as such materials have a typical energetic sensitivity of around <1mJ/cm^2; but not with current, commercially available photopolymers.

4. ECHOLAS – A FAST PRINTER BASED ON STEP AND REPEAT

4.1 Introduction

Since a constant velocity solution cannot be used with photopolymer we are inevitably led back to “step and repeat” being the only possible solution for a viable compact DWDH desktop printer. But how should we achieve the required high hogel write rate? The answer that the Echolas project adopts is *to substantially improve the stage performance and light engine*.

Echolas therefore seeks to design and build a compact linear translation stage which is capable of accelerating and decelerating 30 times per second whilst retaining interferometric stability around the hogel during a sufficiently long time to achieve good fringe contrast.

In addition to the design and construction of this stage, Echolas seeks to completely redesign the traditional bulky optics in the object and reference beam systems of the printer. In particular a new compact apochromatic high-NA objective has been designed, produced and tested. This objective, which has an FOV of 120 degrees and is the size of a large microscope objective, works in conjunction with an apochromatic telecentric telescope system and one or more LCOS panels. In order to accurately control the hogel size, a compact motorised precision aperture has been designed and produced. The reference beam system has likewise been completely redesigned using compact optics, allowing for the automatic switching from table-top to normal wall-mounted hologram modes. The Echolas reference beam system allows a software controlled variable angle system to cater for different illumination distances.

Compact semiconductor lasers of optimum wavelength have been designed and built by Echolas partner Ferdinand-Braun-Institute gmbh (FBH).

The stage and optical systems have been designed to be integrated into a small unit the size of a large desk-mounted photocopier. Comprehensive software has been developed for the data visualization and operation of the printer.

At the time of writing, all component systems of the Echolas project have been designed, manufactured and tested separately; monochromatic test holograms have additionally been written with a standard stage and standard LD lasers combined with the new optics. The next phase, which is currently ongoing, is the integration of the FBH semiconductor lasers and the new stage with the optics. We hope to report results from these tests towards the end of the summer.

4.2 Photopolymer

The refractive index modulation of any holographic material used in digital holography should be maximally high. This is a necessary condition for successfully producing bright and clear full-parallax holograms. For this reason, only photo-polymeric materials were considered for use in Echolas. One of the highest quality and commercially available photo-polymeric materials is a product of the company "Covestro" called "Bayfol," with the code name Bayfol HX200.

This material is a self-developing photopolymer film that can be used to produce reflection and transmission volumetric phase holograms. The material can be exposed (creating the desired interference structure) using laser light in the 440-680 nm spectral range (figure 1), and no additional processing is required to develop the hologram image, except for UV + VIS exposure. For example, wet processing, which is characteristic of classical silver halide materials commonly used in holography, is not required for processing the material. Nor is thermal processing necessary, as is the case with other photopolymers.

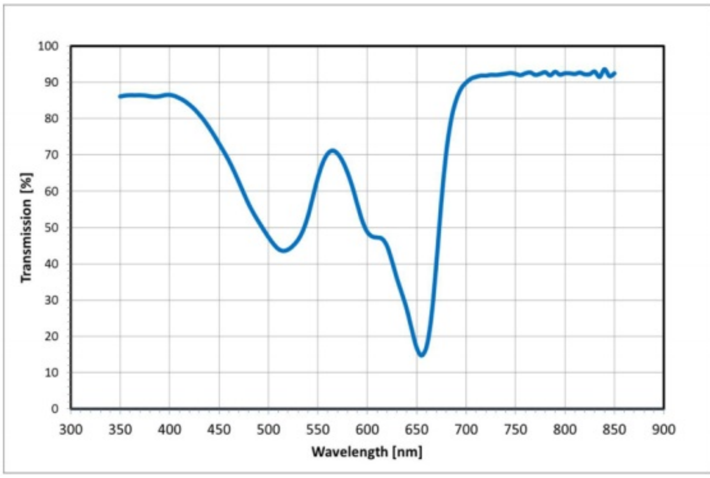

Figure 1: Absorption-transmission characteristic of the photopolymer Bayfol HX200

The structural characteristic of Bayfol® HX200 layers is presented in figure 2.

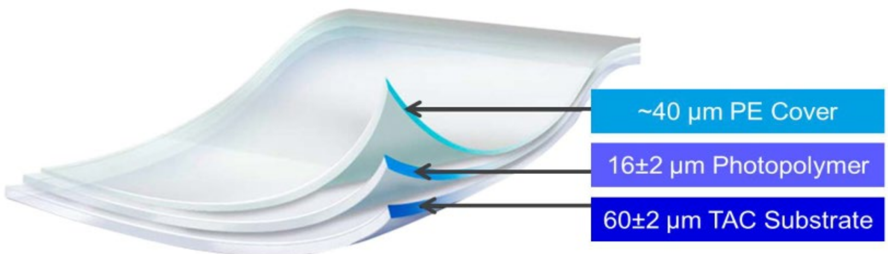

Figure 2: Physical of Structure of Bayfol® HX200

Properties of HX200 Photopolymer

- Standard substrate thickness (on which the photopolymer is coated): 60 ± 2 µm
- Standard photopolymer material thickness: 16 ± 2 µm
- Standard cover film (PE) thickness: 40 µm

Safe light and maximum allowable doses of HX200 Photopolymer

Below are examples of tolerated exposures in a dark room environment (weak yellow light) where it is still possible to work with the material without affecting the final result - safe light for working with the material without affecting holographic properties.

Possible maximum safe light doses (prior to holographic exposure)

- 2.6 µW/cm² for up to 5 minutes with OSRAM PARATHOM DECO CLASSIC, yellow 1 W LED E27
- 0.8 µW/cm² for up to 30 minutes with PHILIPS AccentColor Miniglobe Yellow, yellow 1 W LED E27

Optical properties of HX200 Photopolymer

- Scattering after UV bleaching: < 2%
- Refractive index coefficient of the base (TAC): 1.485
- Refractive index of the photopolymer (unexposed): 1.500
- Refractive index of the photopolymer (after UV bleaching): 1.505

Exposure data for HX200 Photopolymer

- Diffraction efficiency (DE): η > 95%
- Spectral bandwidth (FWHM): > 15 nm
- Exposure dose: approximately 30 mJ/cm² @ λ = 532 nm; I= 4.6 mW/cm²

4.3 RGB Lasers

The RGB laser system is a major part of the Echolas project and is based on ultra-compact semiconductor lasers with monolithically integrated distributed Bragg reflector (DBR), having a single longitudinal mode of operation with a spectral linewidth in the range of 10 MHz. The three colours are generated directly (as for the case of the red laser) or by frequency conversion in periodically poled lithium niobate (PPLN) waveguides (green and blue).

Laser wavelengths of 632 nm (Red), 532 nm (Green) and 460 nm (Blue) were chosen using the constraints of material sensitivity[12], human eye sensitivity[13] and expected replay illumination[14]. The optimal energy density values for R/G/B lasers obtained from experiment are as follows: 632 nm – 16 mJ/cm², 532 nm – 18 mJ/cm², 460 nm – 20 mJ/cm². Target power for each laser was set to ≥20mW.

Figure 3: An example of a 632 nm Echolas laser produced by Echolas partner FBH

4.4 Optical Systems

A simplified object-beam optical system of the Echolas printer is shown in figure 4. The output beams from the three semiconductor lasers are combined to form a white beam with gaussian profile. This is then converted to a top-hat profile at an aperture (AP) using a specially designed non-spherical optical element. The aperture is placed in contact with a lens array which is designed to evenly illuminate a colour-sequential LCOS display (Syndiant) (figure 5). The reflected signal from the LCOS display is then directed by the polarizing beam splitter through an apochromatic telescopic reversal system to an NA=0.86 objective which forms the hogel.

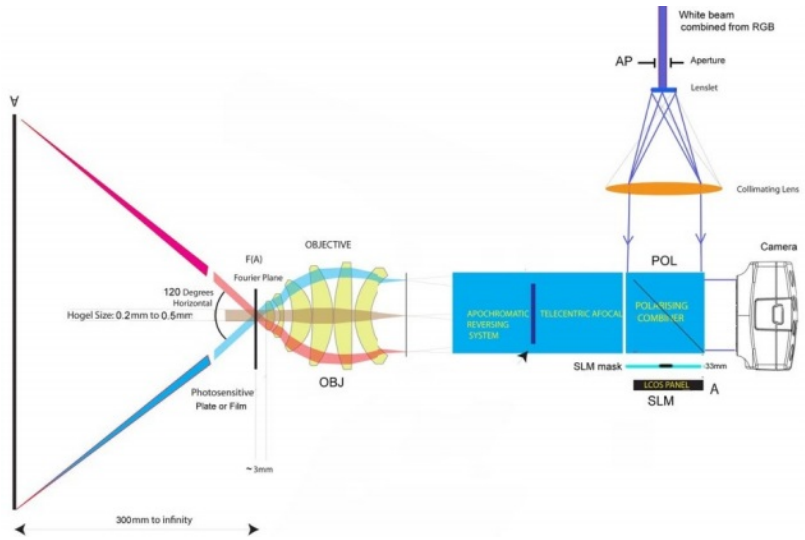

Figure 4: Simplified Object Beam Diagram of the Echolas Printer

Figure 5: Single Panel LCOS (FSC) 0.55" Active Display 4K array of mirrors (3.2 micron pitch)

All the main optical parameters that directly affect the formation the hogel were evaluated, analysed and improved using Zemax^{TM}. Sagittal and tangential curvatures of the image plane and spherical distortions are shown in figure 6. Example ray-intersection distributions at the SLM plane for each wavelength are shown in figure 7.

The angle of view (FOV) of the Echolas objective is 120˚. This directly relates to the numerical aperture (NA) of the lens, which is 0.86. The MTF of the lens is shown in figure 8.

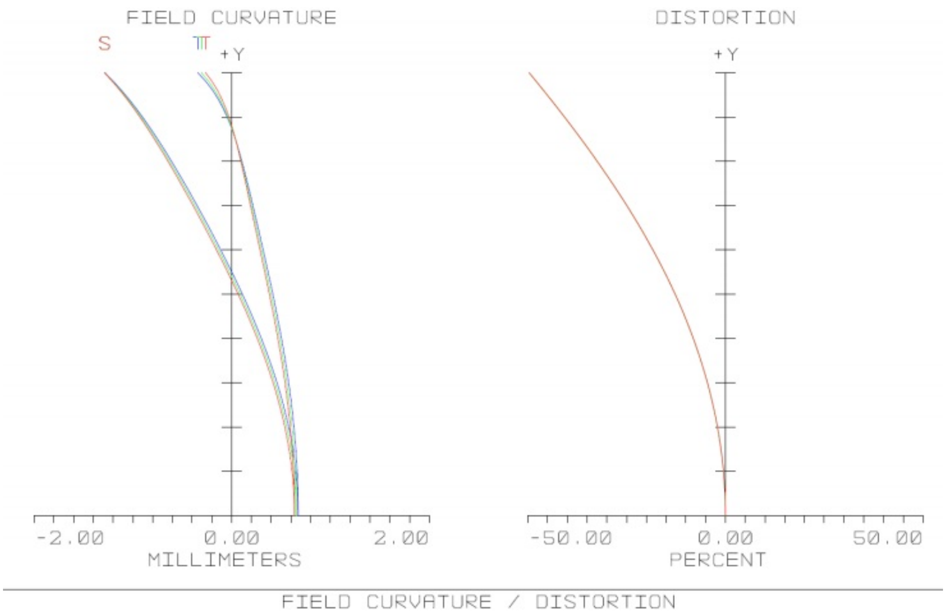

Figure 6: Field Curvature and Distortion of the designed apochromatic objective

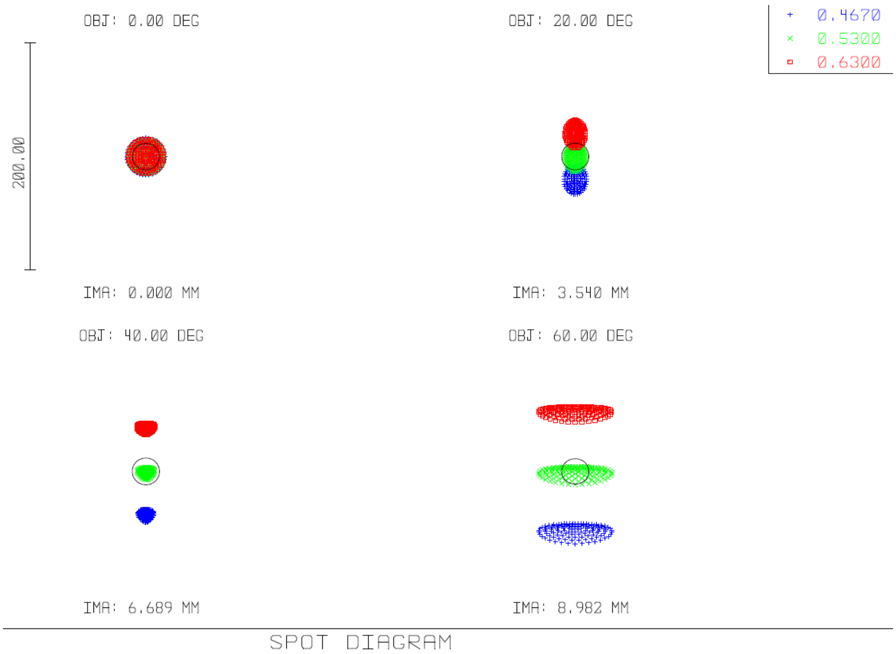

Figure 7: SLM image plane ray-intersection distributions

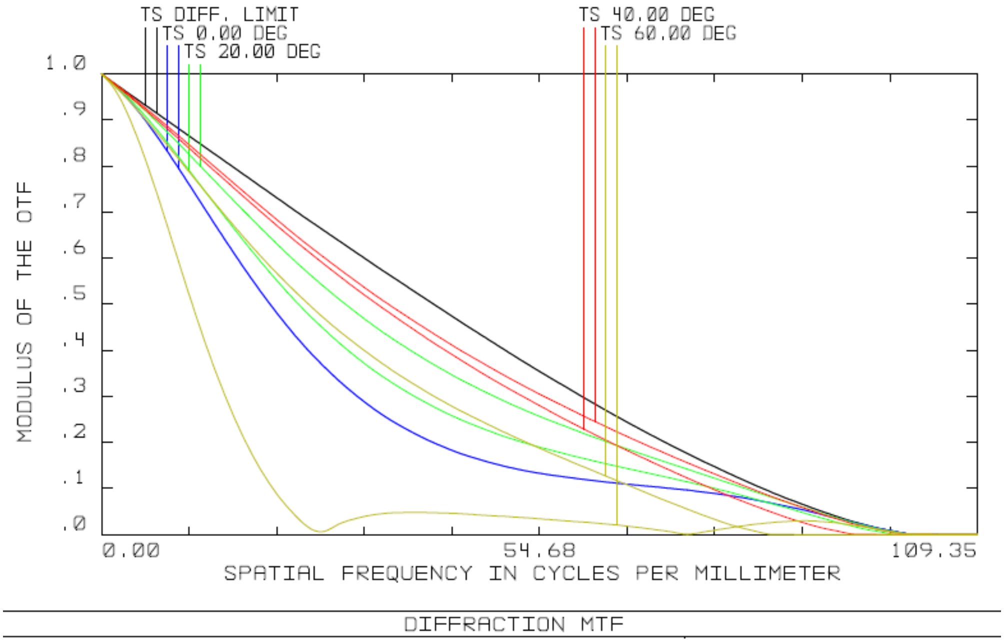

Figure 8: Behavior of the spatial frequency transfer function of the lens system

The refractive index coefficients of the objective lenses and lens assemblies were selected in such a way that the chromatic shift of the formed hogel plane at all three wavelengths would be minimal (figure 9).

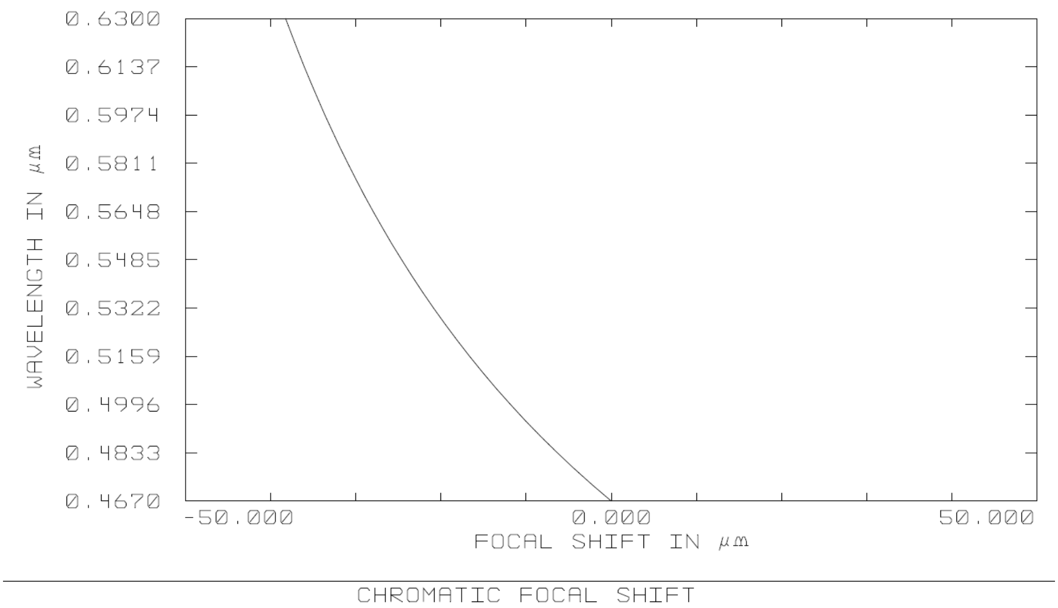

Figure 9: Chromatic Distortion of the designed apochromatic objective

The objective lens system was designed as apochromatic; as such it is suitable for all three selected RGB wavelengths. It is important to note that the hogel formation plane in space must be made as close as possible for all three wavelengths.

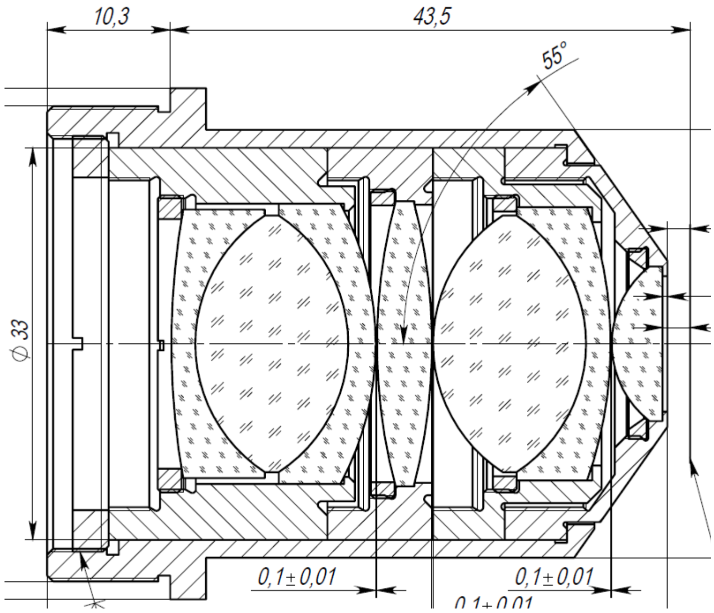

Figure 10: General assembly drawing of the designed apochromatic objective

A telecentric telescope was designed which ensures the transmission of the SLM-modulated image plane to the apochromatic lens, creating intermediate image planes in the common optical system. It is possible to monitor the hogel image plane with the help of a CCD camera. Suitable lenses and CCD cameras were evaluated for this purpose. Since the point ("pixel") of the SLM matrix is only a ~3μm structure, in order to optically separate the details of the objects (corresponding to the spatial frequency transfer function), a multiple-magnification variant of the telescope was chosen (figure. 11).

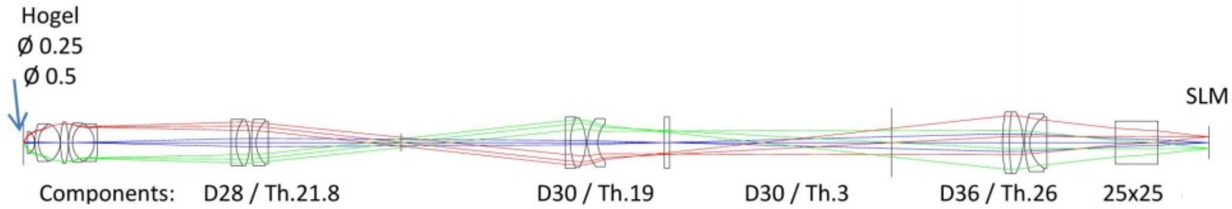

Figure 11: Optical system for modulated objective beam path formation

The optical system of the Echolas printer has been designed to be modular with separate modules for the reference and object beam systems. Figure 12 shows the object beam module. Note the high NA lens (1) which points downwards.

The Echolas printer has been designed to have two hogel printing resolutions – 0.25mm and 0.5mm. The first prototype printer will have a maximum print size of A4. Future printers will be able to produce larger size holograms up to A3. Depending on the size of the selected hologram, the selection of hogel size is realised automatically.

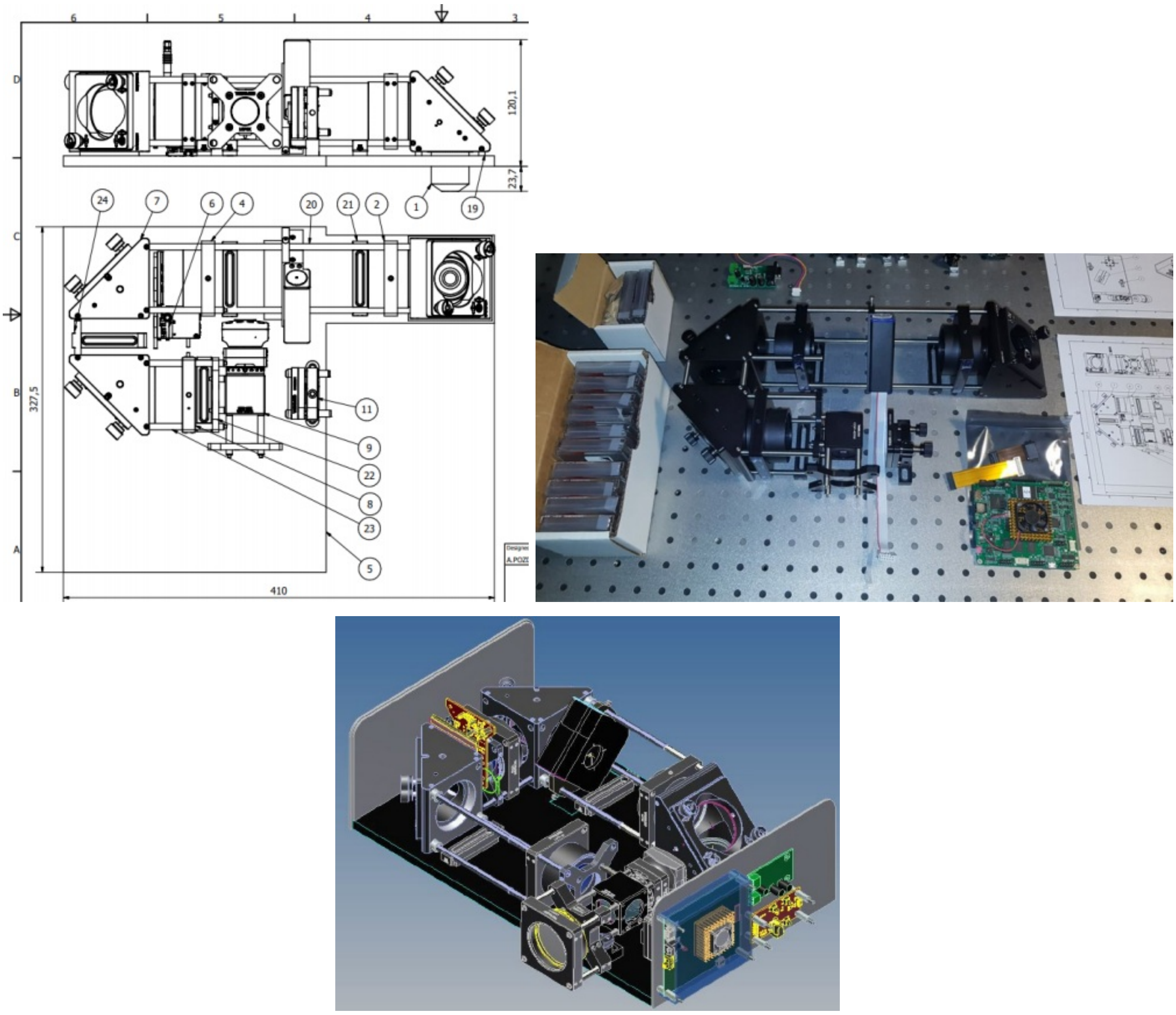

Figure 12: Objective Beam Module

Since ready-made compact electromechanical solutions for changing the hogel resolution are not available on the market, it was decided to design and manufacture such a unit as part of the Echolas project (figure 13).

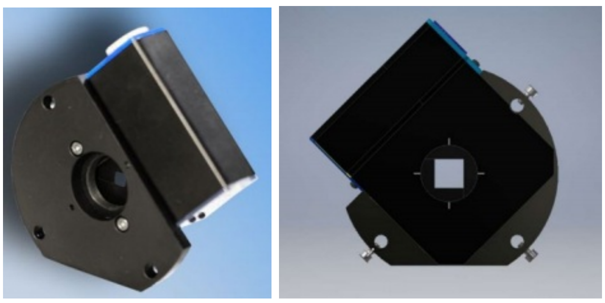

Figure 13: Motorised aperture to define hogel size.

In order to write the hogel a reference beam is required. Depending on whether the final hologram is required to be "table-top" or "wall-mounted" the angle of the reference beam needs to be either perpendicular to the photo-material or at approximately 45 degrees. In addition, the reference beam angle needs to be changed at each hogel to cater for different final illumination geometries. Figure 14 shows a diagram of the Echolas reference beam module.

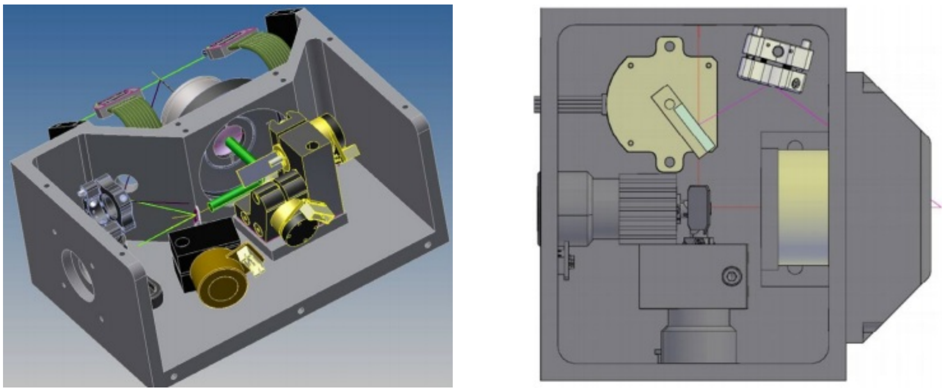

Figure 14: Echolas Reference Beam System

4.5 Motion Platform

In order to reduce injected vibration, the Echolas motion platform employs twin linear actuators coupled in a reverse geometry. Thus, as the main stage accelerates in one direction, a counterweight is accelerated in the opposite direction. By optimizing the position of centres of mass of the stage and the counterweight, the energy injected into the system during acceleration and deceleration can be significantly reduced. Specialised software algorithms are used to stabilise the platform such that interferometric stability may be attained very quickly after the deceleration phase.

The motion platform (figure 15) was developed by Pantec Biosolutions AG utilising state of the art linear motors (Nippon Pulse Motor Co., Ltd), a DC brushless motor (Maxon Motor AG), guiding systems and encoders (Schneeberger AG) and a configurable controller (Pantec Engineering AG). Optical stages, frames and other small mechanical components were from Thorlabs Inc. Key characteristics are

- Maximum velocity = 100 mm/s
- Maximum acceleration = 26000 mm/s^2
- Maximum frequency = 30 Hz
- Repeatable hogel positional accuracy=+/-5 microns
- Rest position stabilisation during illumination
- Impulse compensation
- Trigger functionality
- Adjustable position tolerance

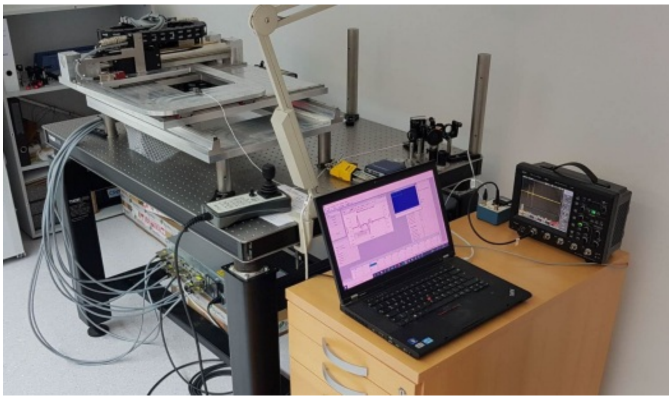

Figure 15: Echolas Motion Platform

The controller of the motion platform accepts a 5V TTL signal which initiates the movement to the next hogel. It also outputs a TTL signal after the hogel position is reached within the desired tolerance. Hogels are written on a line-by-line basis (alternately left to right and right to left).

4.6 First Prototype Tests of Optical System

First prototypes of the reference and object beam optical systems were produced and combined with the Symbian LCOS display. A standard XY motorised stage (Standa UAB) and a LD 532nm SLM laser (Osram PL530) were then used to make first tests of DWDH holograms onto HX200 photopolymer using a standard step and repeat procedure at 0.25Hz. Figure 16 shows the set-up and figure 17 shows a small DWDH test hologram. The set-up was also used to measure the optical characteristics of the printing system and to verify the correct operation of the optical system.

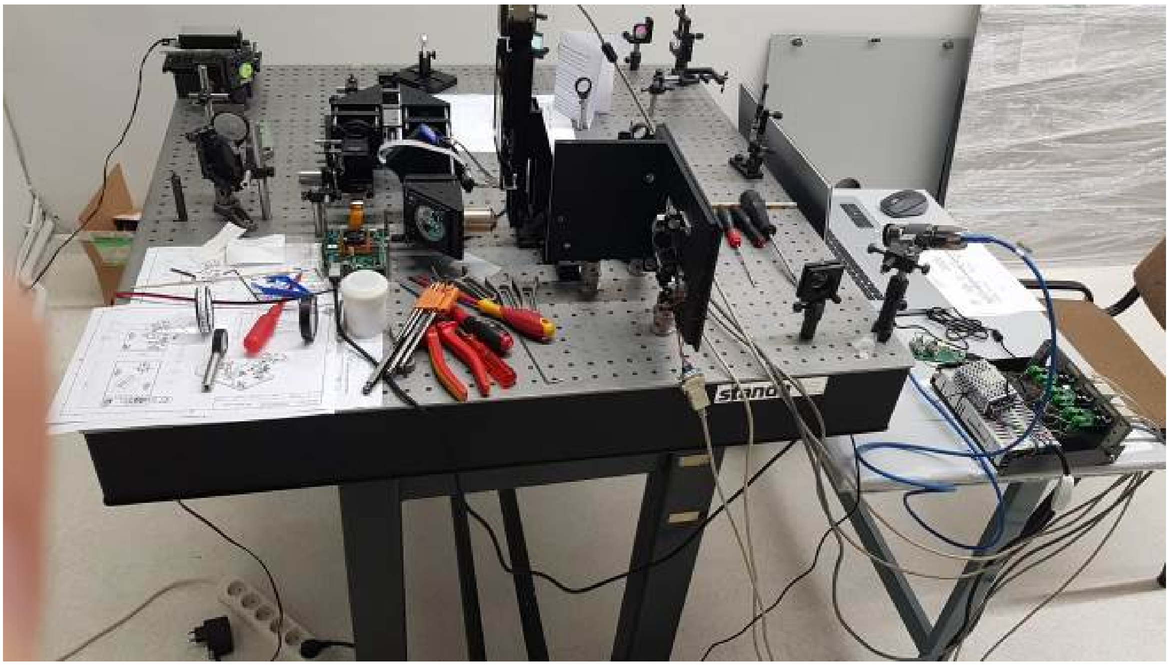

Figure 16: Test printer combining the Echolas Object and Reference beam systems with a standard 2D translation stage, LD SLM 532nm laser and SLM (LCOS). The printer works by “Step and Repeat” at 0.25Hz and can produce either wall-mounted or table-top full-parallax holograms of FOV~120 degrees on HX200 photopolymer.

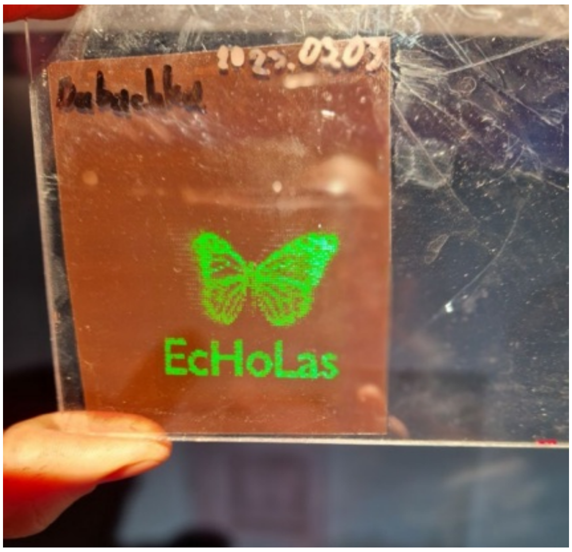

Figure 17: A first small DWDH full parallax hologram created by the printer shown in figure 16 on HX200 photopolymer.

4.7 Integration of Entire Echolas System

The final stage of the Echolas project, which is still ongoing at the time of writing, is the integration of all modules (Echolas semiconductor lasers (R, G and B) – produced by FBH and tested by BFB Berlin – Reference and Object optical modules – produced by Geola Digital UAB – and the motion platform – produced by Pantec Biosolutions AG – into a prototype DWDH printer. Figures 18-21 illustrate how this will be done. The projected size of the final prototype unit is 750x600x500mm and is designed to produce full-parallax large angle-of-view (120 degrees horizontal and vertical) table-top or wall-mounted full-colour holograms on HX200 photopolymer up to a size of ≥A4.

The photosensitive film is moved two-dimensionally by the motion platform; it is mounted and exposed horizontally in the printer. The object beam optical module is mounted above the motion platform and the reference beam system is mounted below.

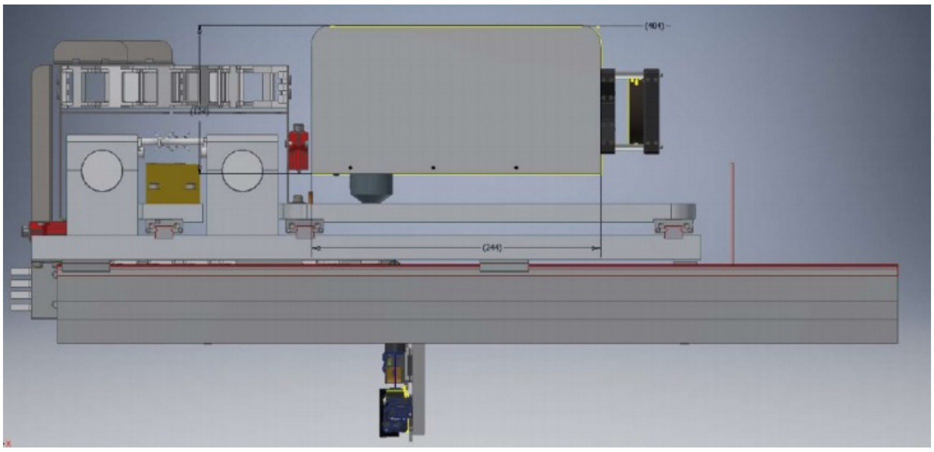

Figure 18: Side view on the Echolas DWDH printer, showing the object beam optical module above the motion platform and the reference beam module below (Breadboard and Case not shown).

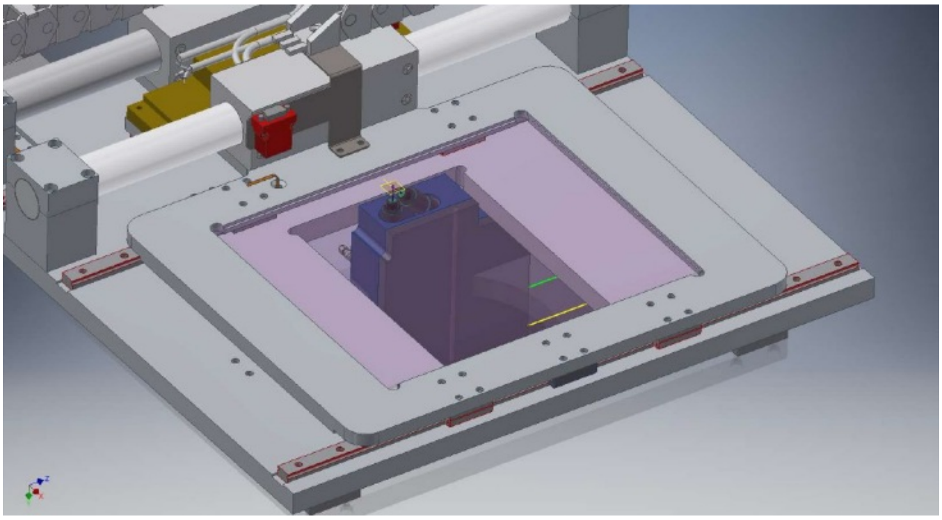

Figure 19: Overhead view of the motion platform showing the photo-material holder below which is visible the reference beam module comprising twin write-heads for table-top and wall-mounted (Breadboard and Case not shown).

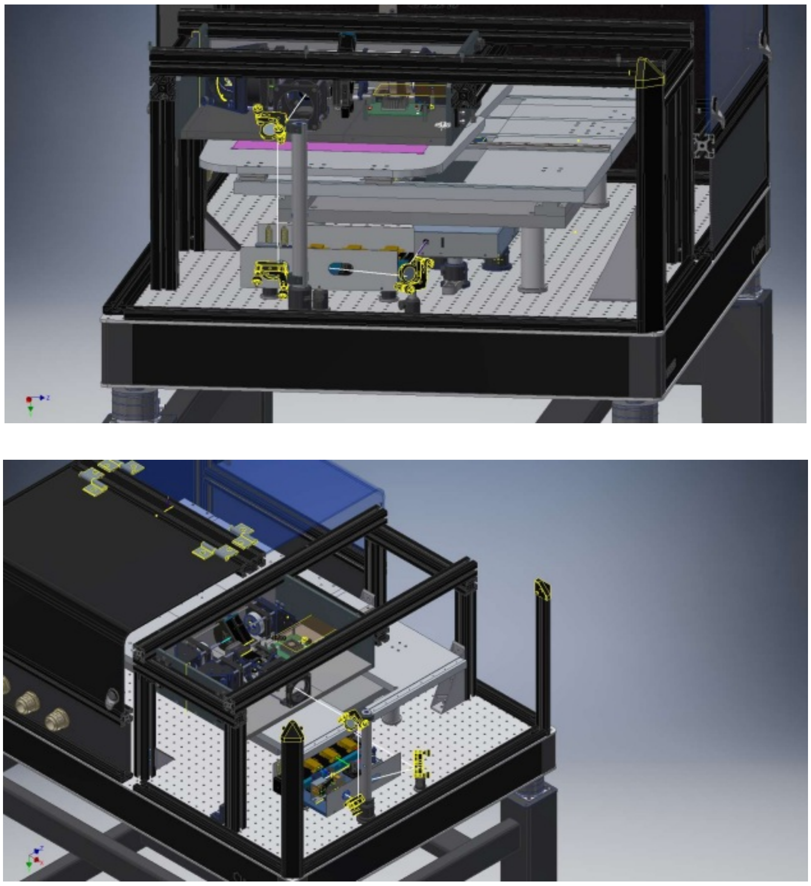

Figure 20: Two views of the Echolas Printer from the side and from above. Note the three semiconductor lasers on the bottom breadboard with beams feeding both the object module (above the motion platform) and reference module (below).

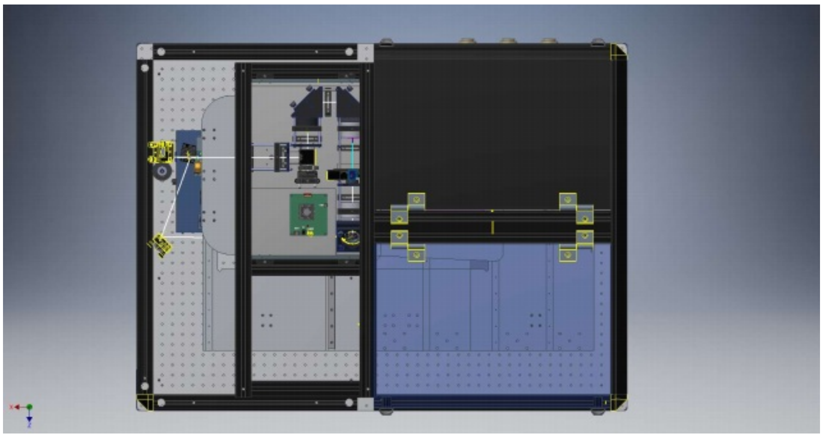

Figure 21: Echolas Printer seen from overhead.

5. CONCLUSIONS

A new compact desktop holographic printer, Echolas, has been designed and results from early tests have been presented. Echolas is a Eurostars Eureka project financed by the European Union. The printer is designed to work with the readily available HX200 colour photopolymer material. A full prototype unit is under construction and is forecast to be ready in July 2023. The Echolas project has aimed to make significant innovations in three areas:

- R, G and B ultra-compact semiconductor laser sources suitable for an DWDH printer
- An advanced DWDH printer optical system
- A unique stabilised motion platform

The Echolas printer is based on 3 miniature DFB/DBR semiconductor lasers each producing > 20mW with good coherence and excellent spatial profiles at 632nm, 532nm and 460nm. The lasers were designed and produced by Echolas partners Ferdinand-Braun-Institut Gmbh and tested by Brilliance Fab Berlin Gmbh, before being shipped to Geola Digital UAB for systems integration.

The Echolas printer is based on the “step-and-repeat” method and aims to write 30 hogels per second at a hogel size of 250 microns. As such a critical component of the Echolas printer is the stabilised motion platform which was developed and tested by Pantec Biosystems AG before being delivered to Geola Digital UAB for systems integration.

The overall printer design targets a compact desktop system allowing the fast production of full colour DWDH holograms of up to A4 format. The entire optical system required was designed from scratch with the specific constraint of size reduction. This process started with the high NA apochromatic objective required to write the hogel. Apochromatic systems were then designed for both the reference beam module and for the required object telescope. The systems were designed with high hologram FOV (>120 degrees vertical and horizontal) in mind and small enough aberration such that all pixels on the 4K SLM are acceptably resolved and high brightness holograms can be achieved. The object and reference optics are designed as separate modules that fit respectively above and below the horizontal motion platform. The reference arm has two modes which can be automatically selected and which switch between “table-top” and “wall-mounted” holograms. The entire printer fits in a box 750x600x500mm.

Initial testing has confirmed correct operation of all component parts and small test holograms have been successfully produced. Further results will be published when full system integration is achieved in latter part of 2023.

ACKNOWLEDGEMENT

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Recent work on direct-write digital holography at geola

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ABSTRACT

Direct-write digital holographic (DWDH) printing is a highly flexible technique for the generation of photoresist masters which are required to produce the metallic shims used for the mass production of holograms in the security and packaging industries. Here we describe a new type of holographic feature which can be combined with any other feature printable using DWDH: full-parallax, full-colour transmission masters containing limited animation. We will also describe a technique to print the fringe pattern of each hogel without using a reference beam. By programming the required fringe calculation algorithm on a graphics card using Cuda we obtain acceptable calculation times. The advantage of using such direct fringe writing is that once again DWDH allows extra features to be written onto a master and combined with other features to produce a stronger security solution. Finally we present results concerning the use of hogel image dithering to improve the grey-scale performance of DWDH printers.

Keywords: image-matrix lithography, holographic printer, digital hologram, DWDH, direct-write holography, 1-step digital holography, security holography, authentication.

1. INTRODUCTION

The technique of writing digital reflection holograms as a matrix of small adjacent elemental holograms (now known as 'hogels') was first demonstrated by Yamaguchi et al[1] (JP) in 1990. These early experiments, although monochromatic, slow, and employing contact apertures, led the way to the development of what is today known as DWDH or Direct-Write Digital Holography[3]. In the late 90's Klug et al[2] (USA) working at Zebra Imaging Inc and Brotherton-Ratcliffe et al[4] (LT) working at Geola UAB improved Yamagushi's technique to allow the production of large-format high-quality full-colour reflection holograms having relatively large hogels (0.8mm-1.6mm). DWDH was subsequently developed at Geola Digital UAB (LT) by Stanislovas Zacharovas et al[5-9] to produce high-resolution digital master holograms for security applications. Here the hogel size was reduced to 100 microns and photoresist was used as the recording medium. This work has led directly to the recent availability of commercial security mastering machines known as DIWO (Direct Write Originator) which complement the well-known techniques of E-beam[10], Dot-Matrix[11-13] and Image-Matrix or Kinemax[14] technology, currently in use by much of the holographic security industry. The combination of DIWO technology with Image-Matrix Lithography and a fast blue pulsed laser allows the rapid writing of all security features from Level 1 to Level 4 in a security master including achromatic and deep 3D horizontal parallax only (HPO) colour images with covert optical security features.

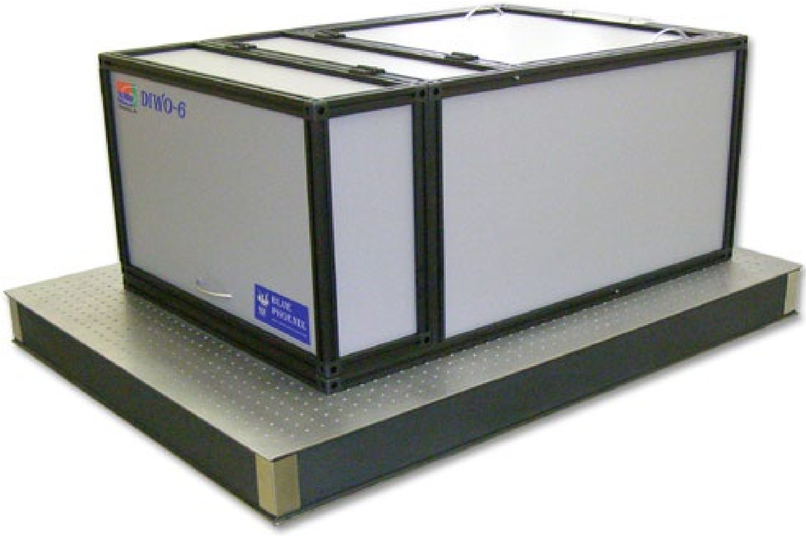
2. CURRENT DWDH SECURITY ORIGINATION

Current DWDH security origination is commercially available through Geola's DIWO-6 originator (Figure 1). This machine typically employs a DPSS SLM 440nm blue pulsed laser operating at 30-120Hz for fast origination of security masters and uses a sequential inscription of holograms, each comprising an ensemble of elemental parts called hogels or holopixels (Figure 2).

As in all DWDH systems the hogel constitutes a fundamental holographic optical unit akin to a pixel in a digital image but differs by offering varying visual representations from different viewing angles, paralleling the behaviour of conventional analogue holographic elements.

Given the limitations of the human eye in discerning small detail, the selected size of the holographic unit (hogel) for master-original printing in DIWO-6 is chosen to be 100x100 microns. This dimension allows the projection of extremely high quality distinct visual perspectives depending on the viewing angle. The underlying mechanism of the recording scheme is depicted in Figure 3.

The high numerical aperture Fourier-Transform objective lens used by DIWO-6 projects a focal point beyond its physical extent. Around this focal spot, light beams emitted from each pixel on a Spatial Light Modulator (SLM) maintain a near identical size and directional consistency. Introducing a reference beam to this focal point allows the inscription of a hogel — a holographic optical element — that, when illuminated, directs light beams along the paths established during recording.



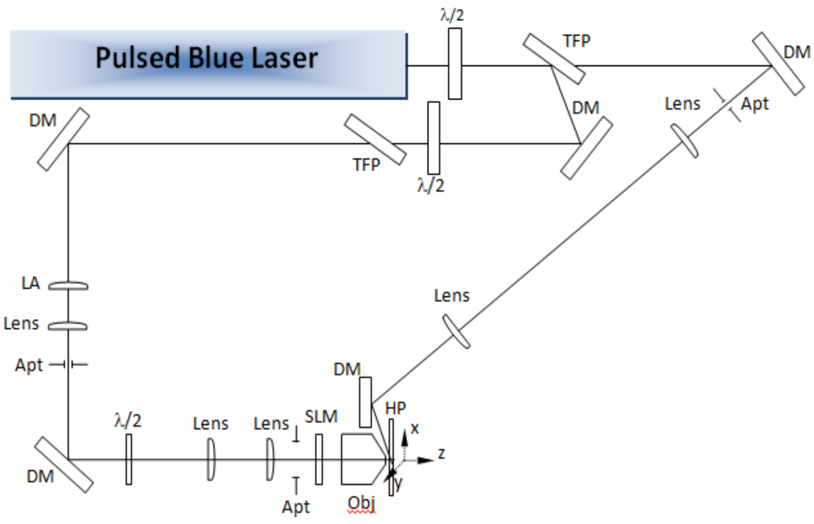


Figure 1: Typical view of DIWO-6 DWDH Originator (above) and simplified optical scheme (below). DM = dielectric mirrors, TFP = thin film polarizer, λ/2 = half wave plate, SLM = spatial light modulator, Obj = Fourier transform objective, Lens = lenses, Apt = aperture, LA = lens array, HP = holographic plate.

For the generation of the SLM image required for the inscription of each specific hogel, Geola employs a collection of parallax-related 2D images of the 3D scene, captured from various viewing angles along a horizontal line (either using a moving digital camera for real world scenes or a virtual camera in CAD software). Corresponding pixels are extracted from each 2D parallax-related image and merged into a new "pixel-swapped" image displayed on the SLM. When illuminated, each hogel then replays these 2D pixel images at their corresponding angles. And the viewer's binocular vision interprets these parallax-related 2D images as a 3D scene (HPO).

An HPO hologram of a 3D object produced using this method, depending on size, usually contains 200 to 800 parallax-related views, thus eliminating any unwanted image transition effects, unless intentionally introduced. This streamlined holographic recording process can swiftly yield effects unachievable with other origination techniques. These include high-resolution 3D images that are:

- Bright and Highly Diffractive
- Capable of Motion Replay
- Deep
- Colour-rich
- Grayscale
- Mixed Grayscale and Colour
- Front and Back illuminated Grayscale and Colour (for transparent films)

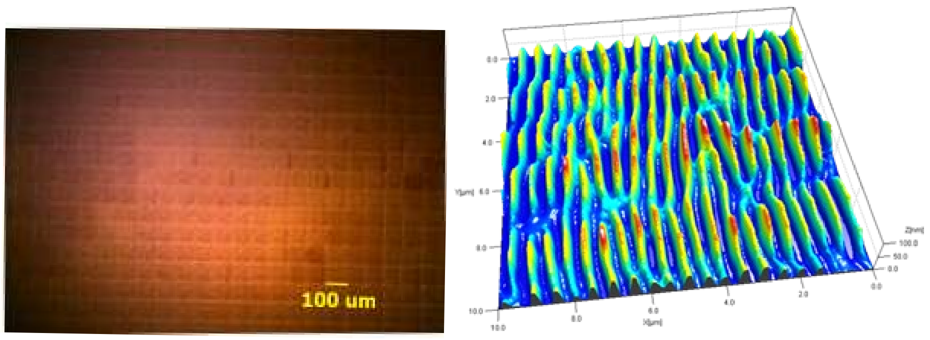


Figure 2: Microphotographs (left) of an embossed 3D image hologram originated with Geola's DIWO-6 – Direct Write Originator and AFM topography scan of a sample 10 micron x 10 micron hologram area (right). Note that the hologram is made up of a raster of 100 micron x 100 micron hogels.

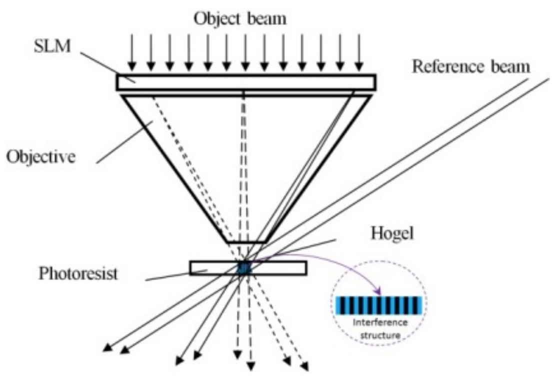


Figure 3: Writing a hogel in a DWDH hologram..

3. ADVANCES IN GEOLA'S DWDH ORIGINATORS

3.1 Full-Parallax Optically-Variable Achromatic 3D Images now available in DWDH Originators

Traditional dogma dictates that reflection holograms are able to support the display of full-parallax images, but transmission holograms must sacrifice the vertical parallax in order to avoid image blurring (as dispersion is much higher in the vertical dimension[2]). Whilst this dogma is certainly true in principle, dispersion of a full parallax DWDH hologram of vanishingly small depth is of course zero. And in fact, the dispersion in the vertical dimension of a hologram with a moderate reference angle (e.g. wall-mounted) only blurs the holographic image unacceptably after a small but finite image depth. In the context of small security and packaging holograms, it turns out that the critical depth available is enough to support optically-variable full-parallax achromatic images with acceptable blurring. Practically this technique can be implemented on existing DIWO-6 machines with only a software upgrade. The technique consists of using a standard full-parallax animated dataset for the required achromatic scene (as used in standard DWDH full-colour full-parallax printers) and using the calculated SLM images as data for the DIWO-6's unique SLM. Figures 4 and 5 show an animated watch hologram produced with the new software created for the DIWO-6. By moving the hologram around in your hands, the image appears clearly full-parallax and in addition the watch hands rotate around the clockface. This feature is a distinct improvement over the HPO images available previously as moving the hologram simulates a real watch. Previous HPO holograms available on photoresist masters showed no motion or parallax change with a vertical tilting of the hologram and as such did not correctly simulate objects such as a watch with moving watch hands.

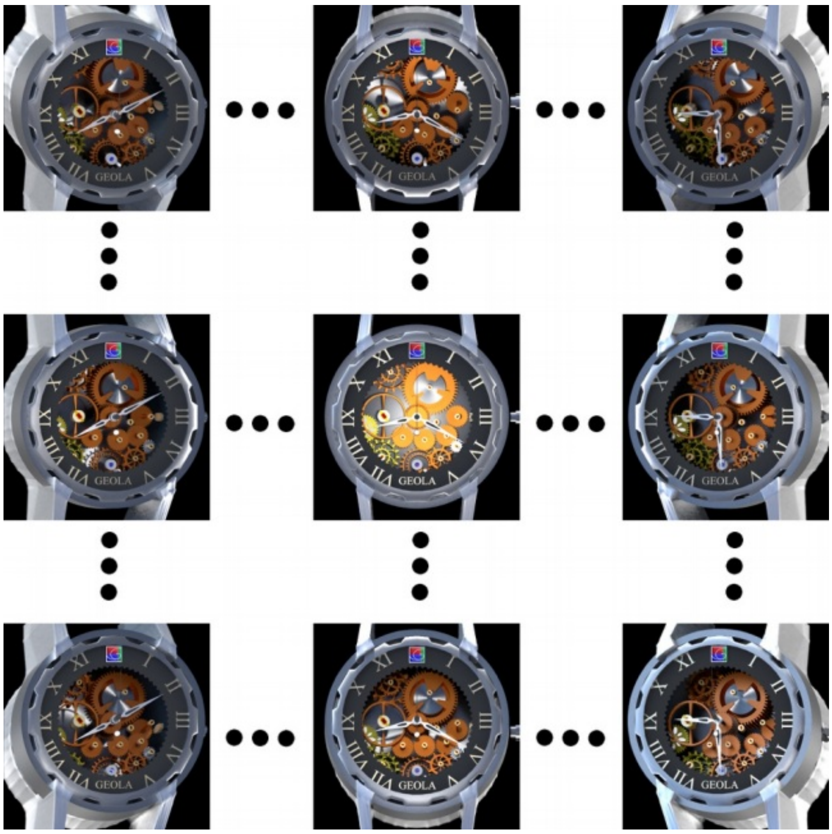


Figure 4: Full-Parallax Perspective View Renders of the hologram of Figure 5. Note that the position of the watch hands are arranged so that as the viewer tilts the hologram up and down and left to right, so the hands rotate around the watch face.

Figure 5: Full-Parallax Optically-Variable Hologram Labels (Left) and Master (Right). Digital DWDH Master made using DIWO-6 originator on photoresist.

3.2 Improving the Gray-Scale

One of the issues up to now of writing DWDH holograms onto photo-resist at the extremely small hogel sizes used in the DIWO-6 has been a less than optimal gray-scale. Geola is now working on releasing a new software version for the DIWO-6 which significantly improves image grayscale. This has been done using a post-processing of the SLM images using Burke's algorithm for dithering. Since the DIWO-6 employs 100 micron hogels, its high-resolution SLM cannot be resolved on replaying the hologram due to digital diffractive blurring[2]. As such dithering the SLM images at the full resolution of the panel produces no angular degradation of the images. However, as with standard 2D dithering, significant improvements to greyscale are observed.

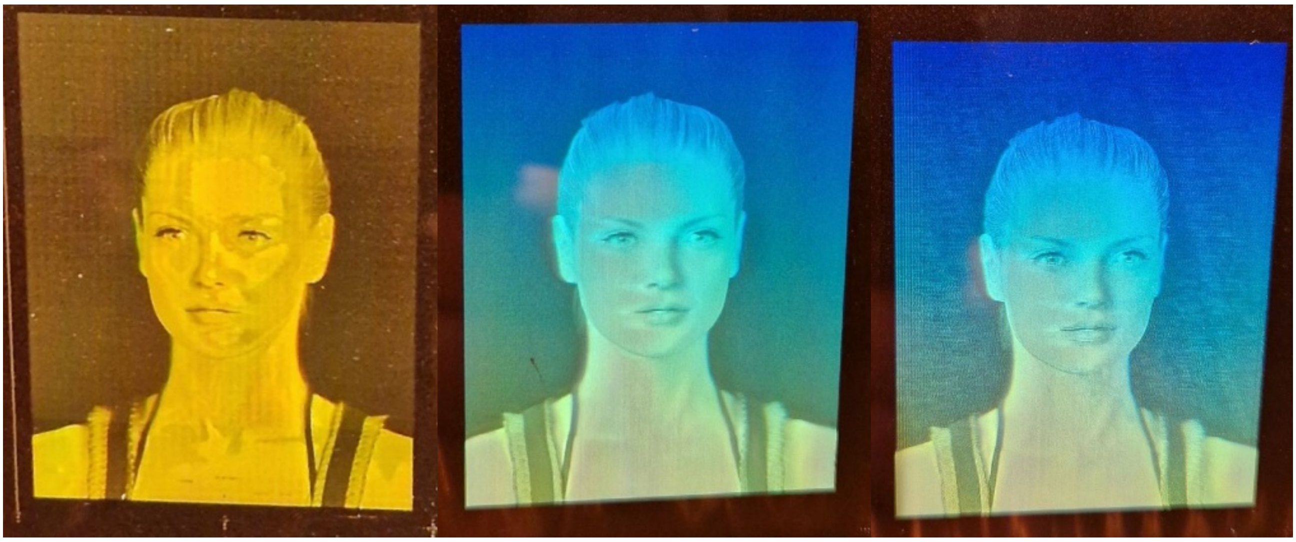


Figure 6: Hologram recorded without Dithering (Left). With Dithering on Perspective View Images (Right). With Dithering on SLM Images (Centre).

Typical results are shown in Figure 6 where on the left can be seen a hologram recorded without dithering. The poor greyscale is clearly visible as patches on the girl's face and chest. The centre photograph shows the result of dithering the SLM images using Burke's algorithm. Not only is the greyscale substantially improved, but importantly there is absolutely no spatial image deterioration. As a comparison, the effect of dithering the raw perspective view images is shown on the right-hand image. Here we can see a clear improvement of the grayscale but at a cost to the spatial resolution.

4. IMPLEMENTING DWDH WITH LITHOGRAPHY

4.1 Image-Matrix versus DWDH

Geola offers two types of security origination systems – the DIWO-6, which has been described above, and the IMP-6 which is an image matrix machine[16]. The two machines are designed to be complimentary and master holograms can be written and over-written on both machines. Together these machines allow all security features covering level 1 to 4 to be produced on the same master (see Figures 7 and 8). The IMP-6 has two modes of operation – holographic and lithographic. These modes are switchable in real-time and so different parts of the shim can use different methods of operation. The highest resolution obtainable is 210,000 dpi. Complex optical security features with holographic images of shallow depth can be printed with the IMP-6 at moderate speed. The DIWO-6 adds deep holographic imagery at faster speeds.

Visibility	Verified by	Diffractive effects and elements	Level
Public (Overt)	Customer	True colour, 2D/3D, Bass-relief, E-beam motion, Guilloches, Lenses, Compass,	Level 1
Simple Aided verification (Obvious)	Specialists	Microtext, Smart glint, Letter lens, Laser readable image, ets	Level 2
Not obviously visible (Covert)	Inspectors	Nanotext, ets.	Level 3
Invisible without very special equipment	Forensic labs	Forensic features (holoframe size, shape, spacing, internal structures of the holoframe, grating period and angle, noise	Level 4

Figure 7: The various levels of security features used in modern security holograms

Figure 8: Described diffractive features (Left) and the actual photoresist master producible by IMP-6 (Right)

4.2 Writing DWDH Holograms using the Image Matrix IMP-6

Currently, in order to print deep holographic images on a security master, including the optically variable full-parallax holograms described above, a DWDH printer such as the DIWO-6 is required. We report here of our first attempts to print DWDH holograms on the image matrix machine IMP-6 in lithography mode using software data processing to calculate the interferometric fringe pattern of individual hogels. These fringe patterns are then imaged directly onto the photoresist using a 405nm laser. In the DIWO-6 the fringe pattern of the hogel is of course produced by the interaction of a reference and object beam.

The fringe pattern calculation is based on the fact the each DWDH hogel on replay essentially projects a 2D image of the recording SLM mask. The distance of the focal plane of this projection from the hogel is usually arranged to be in the range of the optimum viewing distance to infinity. A Fourier or Fresnel transform (as the case may be) of the SLM hogel data therefore defines the fringe pattern of the hogel.

Early attempts to calculate the hogel fringe pattern using Matlab and Fortran required a prohibitively long time. Due to the complexity and size of the fringe calculation, we therefore coded the calculation using CUDA,[16] which thanks to the parallel calculation stream, then brought the calculation time down to a reasonable range on a small PC. As an example, Figure 9 shows full-parallax perspective view data which has then been converted to hogel fringe data as illustrated in Figure 10.

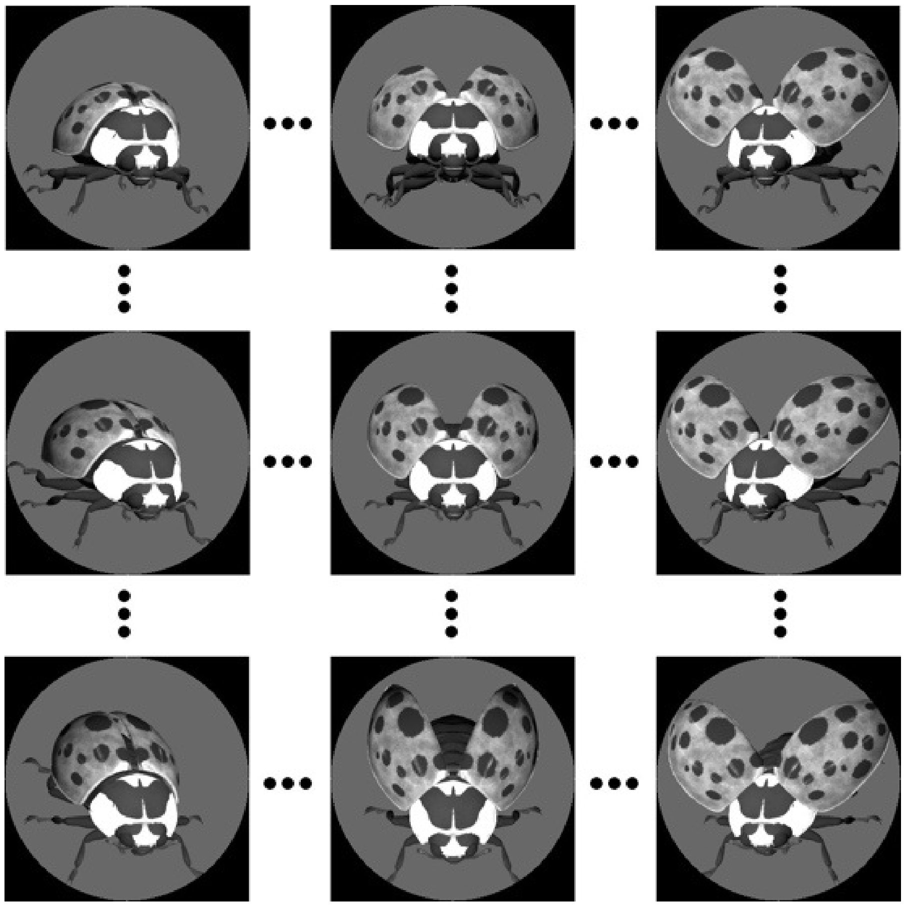


Figure 9: Full Parallax Perspective View Data “LadyBug” used to calculate DWDH hogel fringe patterns for subsequent Lithographic inscription using the image matrix machine, IMP-6.

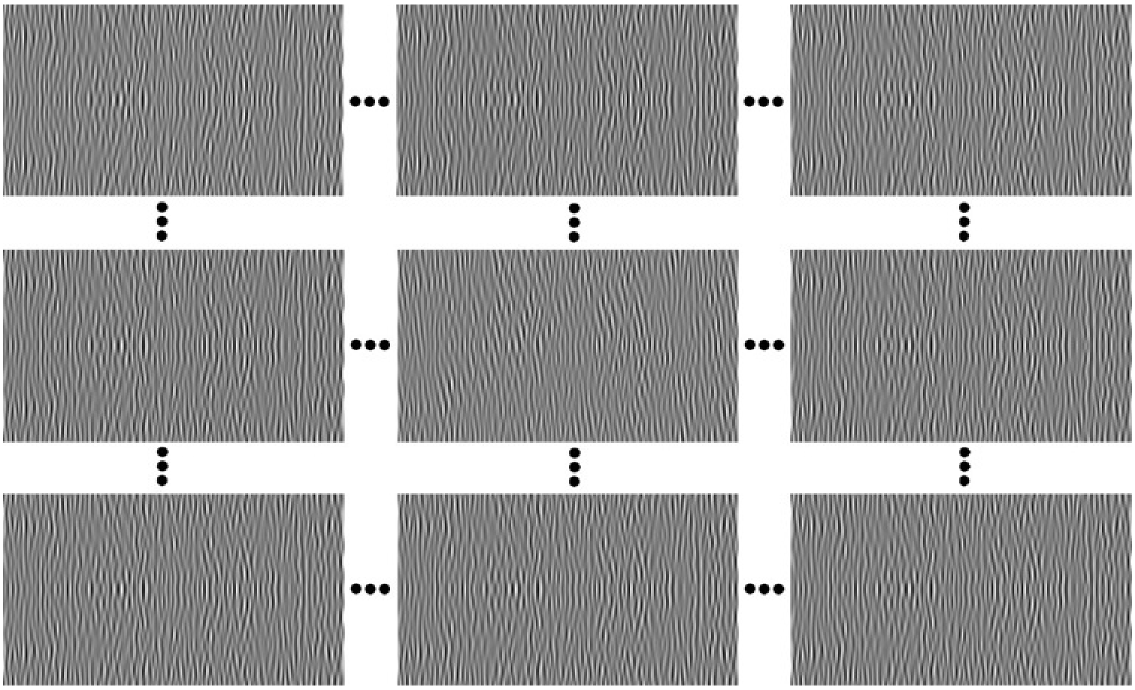


Figure 10: 300 x 300 hogel fringe images calculated by a CUDA algorithm using the data of Figure 9. This fringe data is then used by the IMP-6 to produce a 3cm x 3cm full-parallax achromatic transmission hologram master composed of 300 x 300 hogels each of 100 micron diameter**.**

A simplified scheme of optical lithographic system IMP-6 used in recording the above DWDH fringe patterns shown in Figure 11.

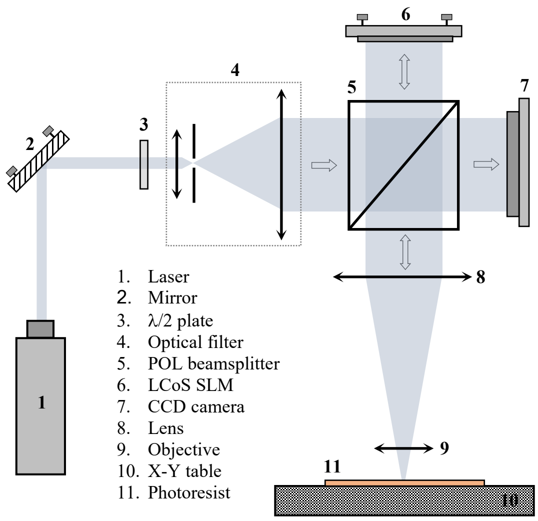


Figure 11: A simplified scheme of optical lithographic system IMP-6 used in recording the above DWDH fringe.

The final hologram and its analysis under a microscope is shown in Figure 12. It must be emphasised that this is a first test only and as such the quality of the hologram is not optimal. We are however optimistic that the quality can be significantly improved; as such DWDH holography features may plausibly be integrated into the IMP-6 in future generations.

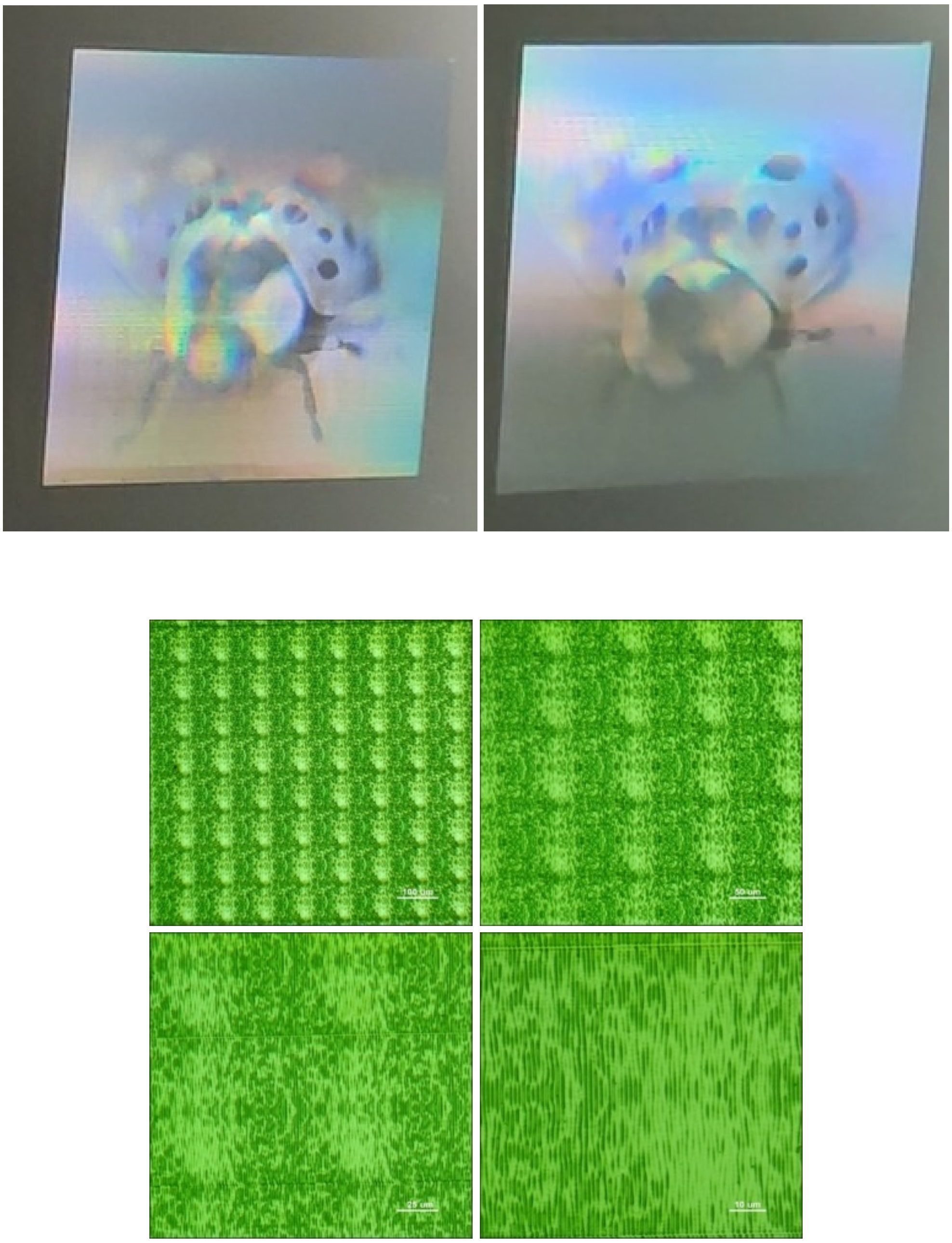


Figure 12: (Above) 2 views of final recorded hologram and 4 views of the analysed structure of a hologram consisting of DOE pixels at different magnifications (Below). Images obtained using a metallurgical microscope under narrow band of green (LED) illumination.

The actual written fringe structure, visible under various magnifications, shows a close similarity to the data pictures presented in Figure 10. We believe that the current weak quality achieved is mainly related with two aspects. Firstly we may have used too much data simplification and this has then resulted in a loss of angular information, and consequently to a restriction of hologram scene depth. Secondly, the achieved results indicate that the optical resolution of the system may need improving; in particular the Rayleigh criterion and the MTF function appear to have been limiting factors to obtaining a better visual appearance of the final hologram made by the IMP-6 originator.

For comparison, the same data as presented in Figure 9 has also been printed using a DIWO-6 machine using the standard DWDH technique. The nickel shim of "LadyBug", with optically recombined data and printed using a 440nm pulsed laser, is presented in Figure 13.

Figure 13: The full parallax “LadyBug” data of Figure 9 produced on DIWO-6 originator using optical recombination. Later said holographic master plate was transferred to nickel via traditional electroforming.

5. CONCLUSIONS

We have presented two new features that will shortly be available as standard in Geola's DWDH security originator DIWO-6. These are:

- the inclusion of full-parallax achromatic optically-variable stereograms (animated) on a security photoresist master and
- the improvement of grayscale on all holograms created by the DIWO-6 machine using dithering of the SLM images by Burke's algorithm.

We have also presented initial work concerning the creation of true DWDH security hologram features using the image matrix IMP-6 machine employing only lithography. Here the DWDH fringe pattern of each hogel is calculated via computer rather than formed by interference. Initial results are promising; further work will be required to see whether the image quality can be increased to a satisfactory level.

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Correction algorithm for wavelength mismatch of sampled wavefield in full-color computer holography

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ABSTRACT

When holographic broadcasting and telecommunication are realized beyond 5G, it is important to correct parameters of holographic 3D image data because it is impractical for various displays to match all parameters to the holographic data. In this paper, algorithm is proposed to correct errors caused in color holographic displays whose wavelengths do not agree with those specified in the transmitted holographic image, i.e., sampled wavefields for primary colors. After theoretical analysis on the effect of the wavelength mismatch, called chromatic aberration in this paper, the proposed correction algorithm is verified through numerical simulations and quantitatively evaluated using several image indexes.

Keywords: Computer-generated hologram, Digital holography, Sampled wavefield, Chromatic aberration

1. INTRODUCTION

Computer holography creating computer-generated holograms (CGH) allows us to reconstruct 3D images of virtual objects. Recently, advances of computation algorithm and devices drive R&D of holographic technology and make it possible to generate giga pixel-scale [1-4] to sub-tera-scale full-parallax CGHs [5, 6]. Along with the progress in telecommunication technology, it is expected that holographic image data can be transmitted through a digital network beyond 5G; Real-time holographic broadcasting and communication will be realized after 6G, where data rates theoretically reach up to 1Tbps.

The transmitted holographic image is displayed by some holographic display device such as near-eye holographic displays [7-9]. However, if there is a parameter mismatch between the transmitted holographic data and the display devices, considerable problem most likely arises in the reconstructed image. For example, a color holographic image is reconstructed by a display that includes light sources whose wavelengths are different from those of holographic image data as shown in Fig. 1, the reconstructed holographic image may suffer from chromatic problems such as color smear. In holographic broadcasting, which sends a specific holographic data to many receivers, it is not practical in various holographic displays to match all parameters to the transmitted data perfectly. Therefore, it is unavoidable to encounter problems due to parameter mismatches unless there is an appropriate correction algorithm. However, unlike ordinary 2D digital images, because holographic 3D images involve various physical information of light, it is not easy to correct the parameter mismatches.

In this paper, we propose correction algorithm for compensating wavelength mismatches in color holographic image data that is sampled wavefields at three wavelengths for three primary colors. Here, note that the sampled wavefield is not a CGH data, which is a fringe pattern generated by interference with reference light. A sampled wavefield is more flexible than CGH fringes because it is free from the influence of reference light used for generating the fringe pattern. Here, we assume that only the wavelength of the light source used in a display device slightly changes from those specified by the sampled wavefield while maintaining the number of samplings and sampling interval. As mentioned in the following section, the wavelength mismatches cause severe color smear in the reconstructed image. This chromatic error is referred to as *chromatic aberration* in this paper. After theoretical analysis on wavelength changes in a sampled wavefield, we propose a method to correct the chromatic aberration. The proposed algorithm is verified through numerical simulations, and its effectiveness is quantitatively evaluated using several image indices of the reconstructed images.

2. ANALYSIS OF CHROMATIC ABERRATION CAUSED BY WAVELENGTH ERRORS

In this paper, it is assumed that only the wavelength of a transmitted wavefield is changed in reconstruction without any change of the phase, amplitude and other parameters. This situation can be expressed as follows:

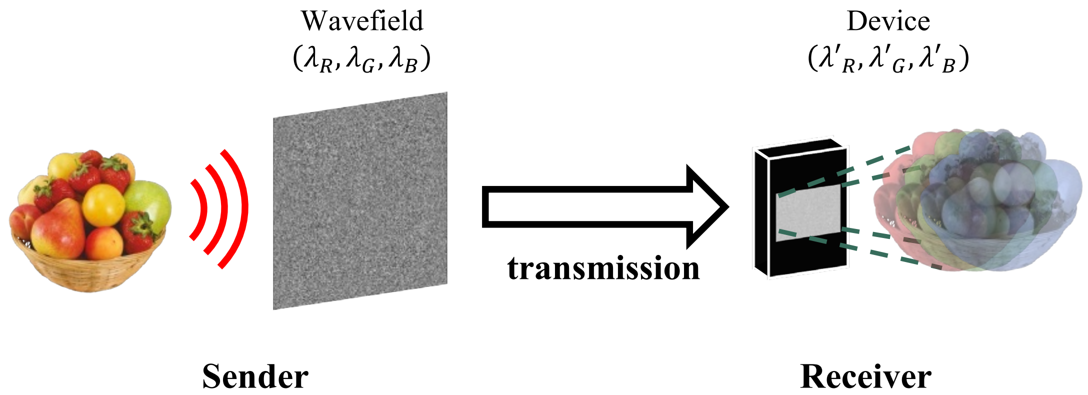


Figure 1. Chromatic problems arising from wavelength errors in transmission of holographic image data.

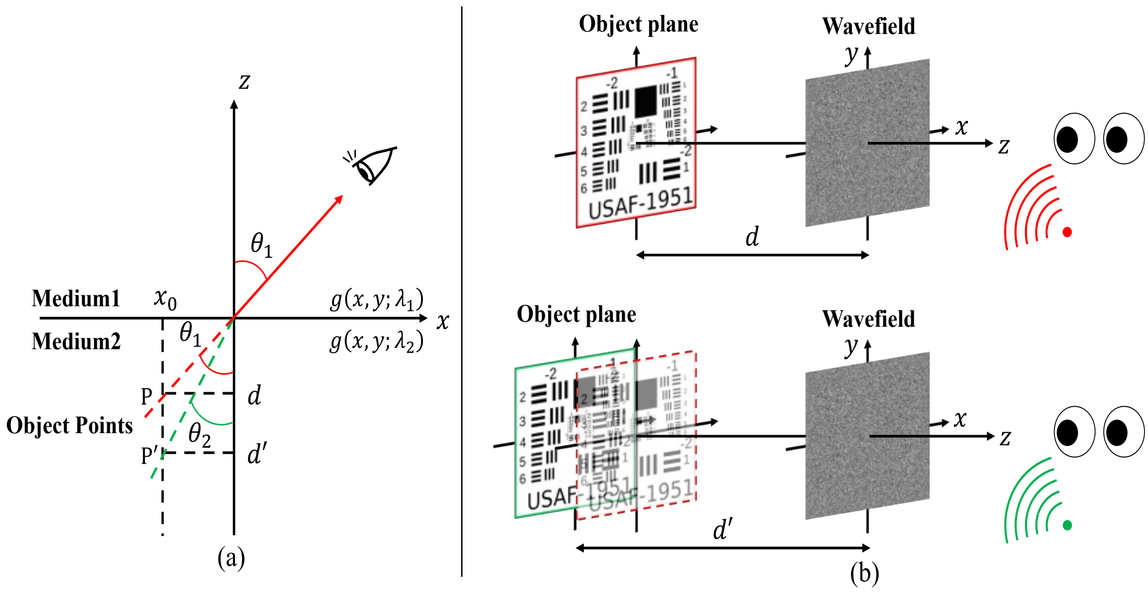


Figure 2. Analysis of the chromatic aberration caused by wavelength errors. (a) Optical refraction at the interface of different media. (b) Change of the depth position of the reconstructed image caused by the wavelength errors.

$$g(x, y; \lambda_1) = g(x, y; \lambda_2) \, . \tag{1}$$

where $g(x, y; \lambda_1)$ is the original sampled wavefield whose wavelength is λ_1, and only the wavefield is changed to λ_2 while maintaining the complex amplitudes. Equation (1), as shown in Fig. 2 (a), can be interpreted as optical refraction at the interface of different media. Here, the boundary surface is in the $(x, y, 0)$ plane and we ignore surface reflection at the boundary.

As shown in Fig. 2 (a), looking at an object image through the wavefield $g(x, y; \lambda_2)$ is equivalent to seeing the object soaked in transparent medium 2, such as water. In underwater, it is well-known that a point P′ located at depth $z = -d'$ appears to be at a shallower position P$(z = -d)$ compared to the actual location. Similarly, the chromatic aberration that arises when reconstructing the original wavefield using different wavelengths can be understood as shift of the reconstructed image along the z-axis, as shown in Fig. 2 (b). This aberration may not pose a significant problem in monochromatic reconstruction because the slight shift may not be detected by human perception. However, in the case of full-color reconstruction using three RGB wavelengths, since the shift amount varies for each wavelength, the aberration most likely leads to color smear. Therefore, it is necessary to compensate for the wavelength error.

According to Snell's law, the refraction shown in Fig. 2 (a) satisfies

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \ . \tag{2}$$

where n_1 and n_2 are refractive indices of the upper and lower media, and determine wavelength in the mediums as follows:

$$\lambda_1 = \frac{\lambda_0}{n_1}, \ \lambda_2 = \frac{\lambda_0}{n_2} \ . \tag{3}$$

Here, λ_0 represents the wavelength in vacuum. By substituting Eq. (3), $\sin\theta_1$ and $\sin\theta_2$, which are geometrically obtained from Fig. 2 (a), into Eq. (2), the depth of object point P' is written as

$$d' = \frac{\lambda_1}{\lambda_2} d \sqrt{1 + \left(\frac{x_0}{d}\right)^2 \left[1 - \left(\frac{\lambda_2}{\lambda_1}\right)^2\right]} \ . \tag{4}$$

The displacement of the object points, $\Delta d = d' - d$, is given by

$$\Delta d = -d \left[1 - \frac{\lambda_1}{\lambda_2} \sqrt{1 + \left(\frac{x_0}{d}\right)^2 \left\{1 - \left(\frac{\lambda_2}{\lambda_1}\right)^2\right\}}\right] . \tag{5}$$

When the size of the object is sufficiently smaller than the reconstruction distance, i.e., satisfies ${x_0}^2 \ll d^2$, or the wavelength change is trivial, i.e., $\lambda_1 \simeq \lambda_2$, Eq. (5) can be simplified as follows:

$$\Delta d \simeq -d \left(1 - \frac{\lambda_1}{\lambda_2}\right) . \tag{6}$$

Therefore, to compensate for the chromatic aberration caused by wavelength errors, we propagate the wavefield $g(x, y; \lambda_2)$ in the *z*-direction as follows:

$$g'(x, y; \lambda_2) = \mathcal{P}_{-\Delta d}\{g(x, y; \lambda_2)\} \ . \tag{7}$$

Here, $\mathcal{P}_{\Delta d}\{\cdot\}$ represents a numerical propagation with a distance of Δd.

3. NUMERICAL EXPERIMENTS

3.1 Experimental setup

Numerical experiments were conducted to verify correction using Eq. (7). The parameters used in the simulations are presented in Table 1. The sampled wavefield used in the simulation was generated from a 2D object arranged at $z = -3$ [cm] ($d = -3$ [cm]), whose optical intensity is provided by the USAF-1951 pattern in the surface. As shown in Fig. 3, sampled wavefields $g_C(x, y; 0, \lambda_C)$ ($C = R, G, \text{or } B$) were calculated using the band-limited angular spectrum method [10] at three wavelengths shown as RGB1 in Table 1.

3.2 Simulated reconstruction

The intensity patterns of the wavefields were numerically reconstructed by propagating the sampled wavefield back to the object position d. Figure 4 (a) shows the reconstructed intensity image where back propagation is carried out using the RGB1 wavelength set. In this case, the original USAF-1951 pattern is reconstructed exactly because we conducted simple round-trip propagation. In contrast, the reconstructed image in (b) shows a kind of color smear, where the sampled wavefields are propagated back to the original position using the RGB2 wavelength set, which are also shown in Table 1.

Table 1. The parameters used in simulation.

Number of samplings	16384×16384
Sampling intervals [μm]	0.8×0.8
Size of object [mm]	11.8×11.8
Object distance, *d* [cm]	3
Set of wavelengths RGB1 [nm]	(640, 532, 457)
Set of wavelengths RGB2 [nm]	(608, 532, 480)

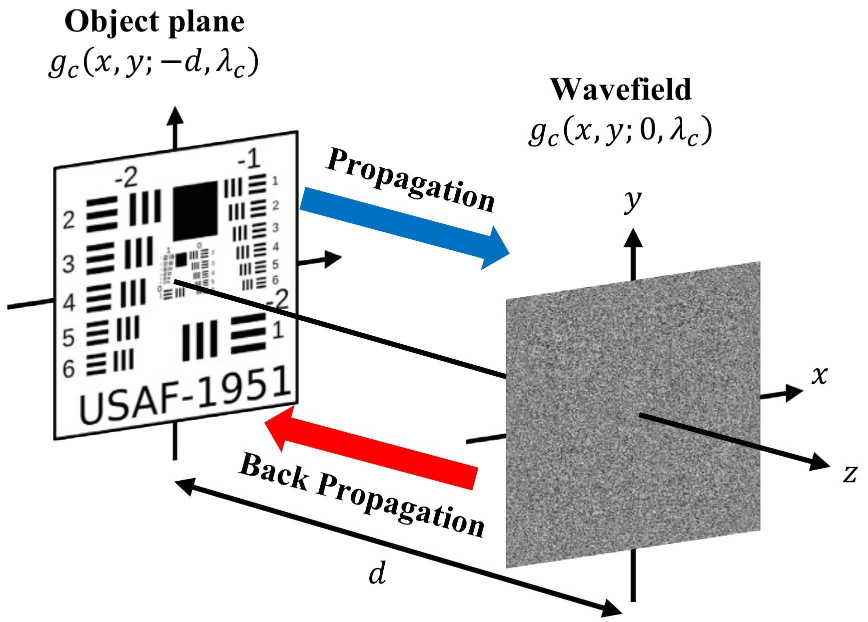
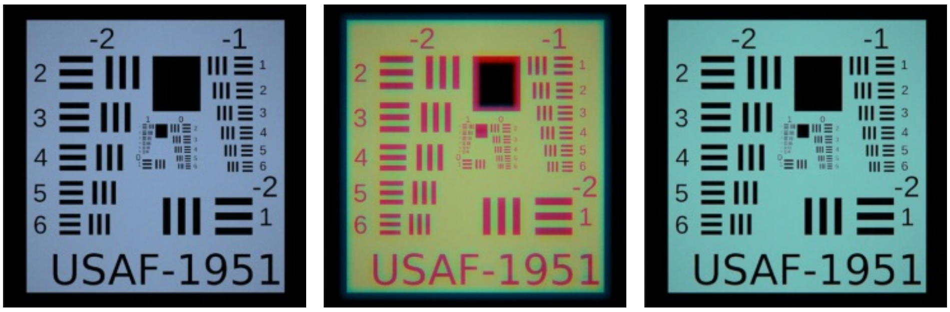


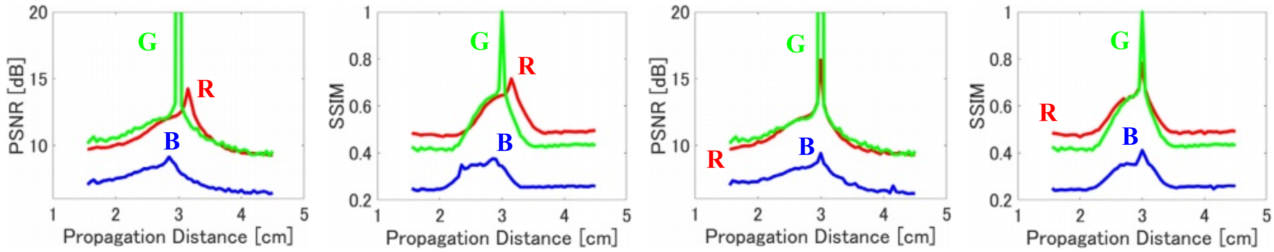
Figure 3. Setup of the numerical experiments.



(a) (b) (c)

Figure 4. Simulated reconstruction by back propagation of (a) the original wavefields with the original RGB1 wavelengths set, (b) the original wavefields with the different wavelengths set, RGB2, and (c) the corrected wavefield using the proposed method with the RGB2 wavelengths set.

In this case, the wavelength for G is the same as that used in generation of the sampled wavefield, while R and B wavelengths are different from original ones. As a result, slight variations are observed in the R and B images. This chromatic aberration causes the color smear in the full-color reconstruction.



(a) (b) (c) (d)

Figure 5. Evaluation of the reconstructed image using PSNR and SSIM: (a) and (b) before correction, and (c) and (d) after correction by the proposed method. In both cases, the sampled wavefields given by the RGB1 wavelengths set are numerically propagated back using the RGB2 wavelengths set.

Figure 4 (c) is the result of simulated reconstruction, where the RGB2 wavelength set is used for the back propagation, but the chromatic aberration is corrected using the proposed method. We can find that a clear reconstructed image similar to Fig. 4 (a) is obtained by the proposed propagation in Eq. (7). Here, note that a slight color change due to the wavelength changes is unavoidable in color reproduction.

3.3 Evaluation of reconstructed images using image indices

To evaluate correction of chromatic aberration using the proposed method, we calculated PSNR and SSIM (structural similarity index measure) of the reconstructed images, obtained by back propagation, for the image in Fig. 4 (a) as the ground truth. Figure 5 (a) and (b) show the PSNR and SSIM of the back propagated images as functions of the propagation distance, where the wavelengths set RGB2 is used in the back propagation. Since the wavelength for G does not change, the peak remains at 3 cm exactly. However, the peaks for R and B are located at 3.15 cm and 2.85 cm, respectively. These peak shifts agree with the expectation by Eq. (4). The images for R and B blur at the original distance of 3 cm. The color smear shown in Fig. 3 (b) is most likely caused by the peak shifts in R and B color.

Figures 5 (c) and (d) also show the PSNR and SSIM of images obtained by back propagation with the wavelengths set RGB2, but the wavefields are corrected using Eq. (7). The evaluation curves for all colors reach the peaks at the same position of 3 cm. As a result, the color smear caused by the chromatic aberration is vanished in Fig. 4 (c). Note that the evaluation values for B are always lower than those of R and G. This is because color variation due to the wavelength change is more remarkable in the B color than other colors.

In conclusion of the numerical experiments, we confirmed the ability of the proposed method to correct chromatic aberration.

4. CONCLUSION

In this paper, we discussed correction algorithm of chromatic aberration caused by difference of wavelengths between transmitted holographic image data, i.e., sampled wavefields and light sources used in the display system. According to our analysis based on analogy of optical refraction, apparent changes occur in axial distance of the object. We obtained the change of axial distance of the reconstructed holographic image and proposed a method to correct the chromatic aberration using numerical propagation of the wavefield. Through simulation and its evaluation by PSNR/SSIM, we quantitatively confirmed that the proposed method successfully corrected the chromatic aberration.

The proposed method is a powerful technique for correcting wavelength errors because of the little computational cost. However, further research is needed for color correction to achieve more accurate color reproduction. In addition, because the proposed method is valid only for 2D objects or thin 3D objects, another technique is probably required for correction of thick 3D objects expanding in the *z*-direction.

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A full-color holographic system based on the RGB-D salient object detection and taylor rayleigh-sommerfeld diffraction point cloud grid algorithms

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ABSTRACT

Real objects-based full-color holographic display systems usually collect data with a depth camera and then modulate the input light source to reconstruct the color three-dimensional scene of the real object. At present, the main problems of the real-time high-quality full-color 3D display are slow speed, low reconstruction quality, and high consumption of hardware resources caused by excessive computing. In this study, a 3D salient object detection model is built at the acquisition step in the full-color holographic system, and a deep network architecture U^2-RAS method is proposed for salient object detection to obtain more efficient and accurate point cloud information. In addition, we propose the Taylor Rayleigh-Sommerfeld diffraction point cloud grid (TR-PCG) algorithm based on the hybrid Taylor Rayleigh-Sommerfeld diffraction algorithm and previous studies on full-color holographic systems. Under the guarantee of reconstruction of real objects' color and position information, we make Taylor expansion on the radial value of Rayleigh-Sommerfeld diffraction in the hologram generation stage while combining with the fast Fourier transform. Therefore, the full-color holographic system can obtain better imaging effects and faster imaging speed. Compared with existing methods, the computational complexity is significantly reduced. We demonstrate the feasibility of the proposed method through experiments.
Keywords: Computer generated holography; Three-dimensional image processing; Holographic System; Salient Object Detection; Color holographic reconstruction; Rayleigh-Sommerfeld algorithm; Taylor expansion

1. INTRODUCTION

1.1 Background

Nowadays, VR and AR display technology is becoming more and more popular, while holographic display technology is one of the most mainstream and promising technologies. Because the real-world scene is mostly three-dimensional (3D) information, while the traditional two-dimensional (2D) devices can only provide 2D plane information without depth clues, which makes human visual perception and understanding ability cannot fully be utilized, and there are problems of lack of information and insufficient authenticity [1]. As a kind of holographic display technology, computer-generated holography (CGH) has become the focus of current research. Compared with traditional optical holography, CGH has many advantages, such as low production cost, fast imaging speed, flexible recording and reproduction, and convenient information storage and transmission. Therefore, CGH display technology has become a hot topic of 3D display in various countries [2,3].

With the arrival of the 5G era, holographic video calls and real-time remote holographic video displays based on computer-generated holograms could become a reality. Realizing high-refresh, high-quality, low-noise, distortion-free color dynamic holographic three-dimensional display for real objects is the only way to the development of calculation holographic three-dimensional display, and it is also an inevitable requirement for holographic three-dimensional display by applications such as metaverse. The challenges faced by high-quality holographic dynamic 3D displays mainly include some questions: the difficulty of collecting data in real-time, the low calculation speed, the insufficient quality of hologram reconstruction, the limited performance of wavefront modulation devices, and the lack of 3D content sources, therefore it is difficult to meet the actual needs [4]. Therefore, the research of improving the adaptability of hologram generation algorithms and improving the quality of reconstructed images have become urgent problems to be solved in computing holographic three-dimensional display technology. It should be solved in the practical process of computing holographic displays.

1.2 Relate Works

With the improvement of depth camera technology, it becomes very convenient to collect information of 3D real objects with depth camera, followed by the urgent need for personalized editing and processing of these 3D information. Salient object detection (SOD) is an image preprocessing step that simulates human visual attention mechanisms in the field of computer vision. By detecting the area of our most interest in the image, we can filter out redundant background information, which can effectively reduce the complexity of massive information processing. This is also important for 3D data in holographic display systems [5]. In the previously constructed color holographic display system, we use a depth camera to obtain depth and color information from real objects, and then use the traditional Region of Interest (ROI) algorithm to generate a color point cloud model to mesh the point cloud to adapt to the Fast Fourier Transform algorithm (FFT). However, the traditional ROI algorithm has a lot of redundancy and drawbacks, which limit the further improvement of the processing performance of the acquisition step.

In the past two decades, a large number of salient object detection methods have been proposed, and salient object detection is widely defined as the problem of capturing rare and unique elements from images. The extensive application of convolutional neural network (CNN) in different image tasks (such as object detection, semantic segmentation, edge detection, etc.) provides a new idea for salient object detection and shows surprising improvement in some work [6,7]. After 2016, many salient object detection models began to be implemented based on FCNs. Based on the Holistically-nested edge detection (HED) [8], Hou et al. [9] proposed a concise and effective strong supervised short-term structure. This model connects the enlarged deep feature map with all the shallow feature maps before it, so that it effectively uses the high-level features and low-level features, blending their advantages, and converting the high-level features into shallower side output layers, which can help them better locate the most significant areas, while the shallower side output layer can learn rich low-level features. Wang et al. [10] proposed a two-part model, namely the cyclically located network (RLN) and the boundary refinement network (BRN). The model helps to better locate salient objects by repeatedly focusing on the spatial distribution of various scenes while helping to refine the saliency map through the relationship between each pixel and its neighbors. In recent years, salient object detection efforts have focused on designing more complex feature fusion network structures to better fuse features and improve model effectiveness. However, most of the existing deep saliency models are fine-tuned by image classification networks, so they unconsciously focus on the regions with high response values during the residual learning process, making it difficult to capture the residual details (such as object boundaries and other undetected object parts).

In order to speed up the calculation, scholars have done a lot of research. The authors once proposed a multi-camera holographic system based on heterogeneous sampled two-dimensional images and A Full-Color Holographic System Based on Taylor Rayleigh–Sommerfeld Diffraction Point Cloud Grid Algorithm point cloud grid algorithm (S-PCG). Compared with the traditional wavefront recording plane method, the quality of the recon-structed images is significantly improved and the computational complexity is greatly reduced [11]. The authors also proposed a point cloud grid (PCG) algorithm to speed up the generation speed of computing hologram for real objects, and then proposed the divided point cloud gridding (D-PCG) to improve the quality and accelerate the speed of full-color holographic system [12]. In order to improve the quality of reconstruction, the author also proposed a holographic system based on multi-depth camera to flexibly and effectively obtain full-color reconstruction images [13].

1.3 Research of our paper

Therefore, this paper uses residual learning to learn the side output residual features for salience refinement [14], introduces U^2-Net to capture more contextual information from different scales. Based on the hybrid Taylor Rayleigh-Sommerfeld diffraction algorithm proposed by CHEN et al. and the author's previous research on full-color holographic systems, we propose a method called Taylor Rayleigh-Sommerfeld point cloud grid (TR-PCG) to achieve the rapid generation of holograms, finally building a color holographic three-dimensional real-time display system for real objects. We promote the processing speed and image accuracy of the holographic system at the acquisition step, accelerate the calculation speed of the hologram generation stage, ensure the quality of the panchromatic reconstructed image, and further improve the performance of the system.

2. THEORY

2.1 Full-color holographic system

In this paper, aiming at the two key problems of the acceleration of the 3D information acquisition step and the acceleration of the hologram generation step in the real-time holographic 3D display technology, the research on the real-time color holographic technology facing real objects is deeply carried out by introducing the salient object detection and Taylor Rayleigh-Sommerfeld diffraction point cloud grid algorithm (TR-PCG). The research content of this paper is shown in Figure 1. The full-color holographic system consists of three steps: (1) 3D information acquisition and preprocessing, (2) hologram generation, and (3) color reconstruction. In step 1, the research scheme of three-dimensional significant object detection is adopted, and the Taylor Rayleigh-Sommerfeld diffraction point cloud grid algorithm is used in the middle of step 1 and step 2 to improve the calculation speed of holograms

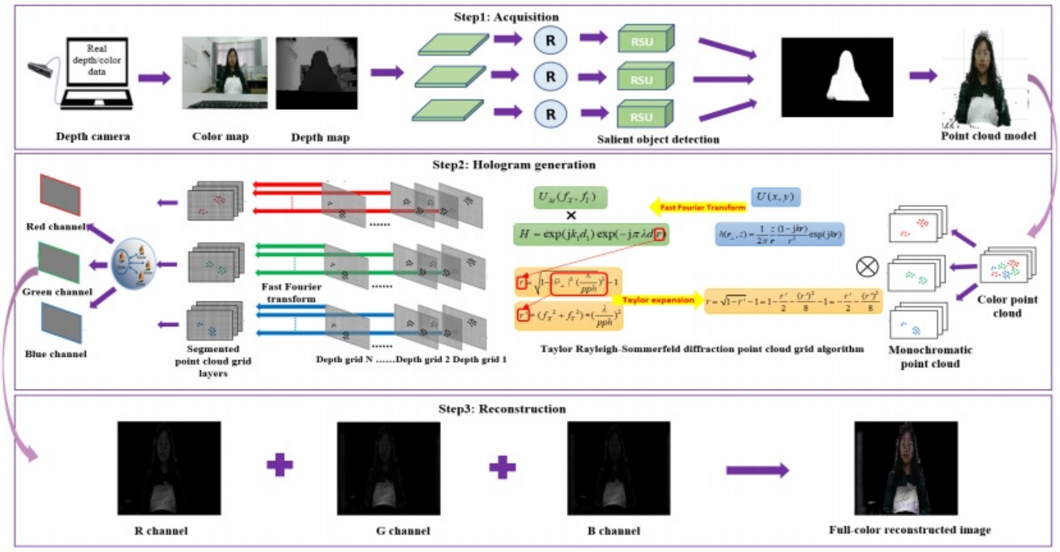

Figure 1. Schematic diagram of full-color holographic system

2.2 Salient object detection

The 3D salient object detection network proposed in this paper is based on Holistically nested edge detection (HED) architecture and U-Net. It is an accurate and compact deep salient object detection network, mainly composed of reverse attention and residual learning (RAS) and ReSidual U-blocks (RSU). The overall framework is shown in Figure 2.

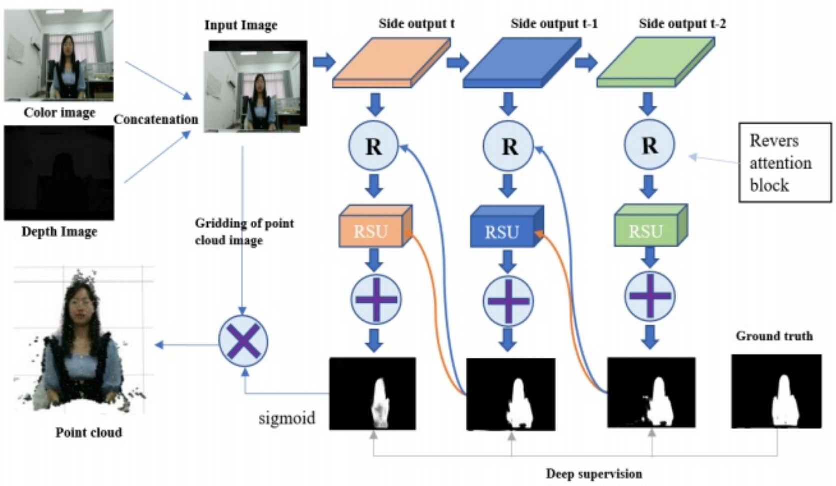

Figure 2. Architecture of salient target detection network

Put the color image and depth image into the detection network, use residual learning to learn the residual features of the side output for the deepest roughness salient prediction, and apply deep supervision to learn the residual features, instead of directly learning the multi-scale saliency features in different side output stages, so as to achieve the effect of making the model lighter under the premise of ensuring accuracy. Formally, given the upsampled input saliency map by a factor of 2 in the side-output stage, and the residual feature learned in the side-output stage, then the deep supervision can be formulated as:

$$\begin{cases} \{S_{t+1}\}^{up\times 2^{t+1}} \approx G_T \\ \{S_{t+1}^{up} + R_t\}^{up\times 2^t} = \{S_t\}^{up\times 2^t} \approx G_T \end{cases}, \quad (1)$$

where S_t is the output of the residual unit and G_T is ground truth, $up\times 2^t$ denotes the upsample operation by a factor 2^t, which is implemented by the same bilinear interpolation with HED [8]. Then the prediction of the shallowest side output is then sent to the sigmoid layer for output.

The reverse attention mechanism is introduced to guide the feature learning of each side output layer. Starting from the rough saliency map with high semantic confidence but low resolution generated at the bottom layer, the current predicted saliency region is deleted from the side output feature to guide the entire network to discover supplementary object regions and details in turn, and the attention weight is applied to each side output layer in a top-down manner.

For the part of the detected object that is significant, the mask map is taken from the lower feature map, so that only the detection of the currently undetected is completed, and there is no doubt about whether the current detection is superfluous. This makes the network training convergence very fast, if the mask map effect is good, output 0, which is also the advantage of residual networks. However, if the saliency map has redundant parts that cannot be corrected, it will inevitably lead to some errors. Of course, this is also related to the current salient object detection is mainly detected by the incomplete contour of the object. Therefore, this paper cites the ReSidual U-blocks (RSU) module, which is able to acquire contextual information at different scales without reducing the resolution of the feature map. In the original U-Net structure, an RSU module is filled in each stage to form a nested U-shaped structure, called U^2-Net [15]. The RSU replaces the ordinary single-stream convolution with a structure similar to U-Net and the original features with local features transformed by the weight layer:

$$H_{RSU}(x) = u(F_1(x)) + F_1(x), \quad (3)$$

where u represents the multi-layer U-structure illustrated. This design enables the network to extract features directly from multiple scales for each residual block, increasing the network depth without increasing the computational intensity.

We combine the RAS module and RSU module and nest them on U-Net to obtain a novel and efficient network architecture, called U^2-RAS. U^2-RAS is designed for SOD without using any pre-trained backbones from image classification. It can be trained from scratch to achieve competitive performance. Secondly, the new architecture enables the network to be more in-depth and obtain high resolution without significantly increasing memory and computing costs.

Then, the point cloud is generated from the color image and depth image of the object. The point cloud generated by the depth camera usually contains a large amount of depth information, as shown in Figure 1 (step 2). However, on the z-axis of the point cloud, the depth difference between each point is constant. The point cloud can be classified into multiple sublayers using depth information. Once the point cloud is classified, the point cloud model can be resampled and converted to a deep mesh.

Finally, the point cloud model of salient objects is obtained by multiplying the gridded point cloud model and the prediction detection map output from the sigmoid layer.

2.3 Theoretical derivation of the TR-PCG algorithm

The point cloud grid method generally consists of three steps. First, the depth camera captures point clouds containing depth information. Next, each point of the same depth is matched with a depth grid node, that is, each depth grid contains all points at the same depth. Finally, according to the coordinates of each layer in the generated grid, diffraction calculation is carried out for each layer with FFT, and the final CGH is obtained.

So on the basis of PCG, we propose TR-PCG. We will only discuss the holographic generation stage here, and refer to [16] for a detailed introduction of other stages.

An FFT is performed on each grid to calculate the diffraction and obtain three computer generation holograms, one for each of the red, green and blue channels. It is necessary to calculate the complex value of the light field at each sampling point. We perform Taylor expansion for the radial value r in the convolution based on FFT to realize relatively high-speed discrete Fourier transform of the object light field.

According to the geometric relationship, the radial value r in the frequency domain satisfies the following formula:

$$r=\sqrt{({f_X}^2+{f_Y}^2)*(\frac{\lambda}{pph})^2}, \tag{11}$$

where f_X and f_Y are the frequencies in the frequency domain, λ is the wavelength and pph is the spacing of pixels.

According to the Rayleigh-Sommerfeld diffraction formula, the fourier transform is applied to the point spread function h to obtain the transfer function H in the spatial spectrum domain, as shown in the following formula:

$$H=\exp(\mathrm{j}k_1d_1)\exp(-\mathrm{j}\pi\lambda d_1 r), \tag{13}$$

where k_1 is the wave vector of the red wave, λ is the wavelength of the red wave and d_1 is as shown in the following equation:

$$d_1=d-Cut*\frac{sam\_int}{2}, \tag{14}$$

where d is the distance to generate the hologram and Cut is the segmented point cloud grids.

What's more, r is as follows:

$$r=\sqrt{1-|\rho_\perp|^2(\frac{\lambda}{pph})^2}-1, \tag{15}$$

where $|\rho_\perp|^2=({f_X}^2+{f_Y}^2)$.

For convenience, here we call r' as follows:

$$r'=({f_X}^2+{f_Y}^2)*(\frac{\lambda}{pph})^2, \tag{16}$$

So the relationship between r and r' is:

$$r=\sqrt{1-r'}-1, \tag{17}$$

According to the Taylor expansion formula, so r is expanded as follows:

$$r=\sqrt{1-r'}-1=1-\frac{r'}{2}-\frac{(r')^2}{8}-1=-\frac{r'}{2}-\frac{(r')^2}{8}, \tag{19}$$

According to the findings of the experiment, the reconstruction image with shorter computation time and higher quality can be obtained when retaining to the quadratic term. When retaining to the cubic term, the reconstruction quality is similar to that of the quadratic term. Relative to the increase of reconstruction time, the reconstruction quality is not significantly improved.

Since we need the results in the time domain, we should take inverse Fourier transform of the answer in the frequency domain. The final result is shown in the following equation:

$$H_{Depth\_grid\_N}=F^{-1}\{U_M(f_X,f_Y)*H\}, \tag{20}$$

where $H_{Depth\_grid\_N}$ represents the hologram of the depth grids in channel X (X=red/green/blue), $U_M(f_X,f_Y)$ is the optical field information of channels red, green and blue, and H is the angular spectrum.

Finally, the hologram Hol is obtained by superposition:

$$Hol=H_{Depth\_grid\_1}+H_{Depth\_grid\_2}+......+H_{Depth\_grid\_N}, \tag{21}$$

The hologram generation stage of TR-PCG is shown in Figure 3.

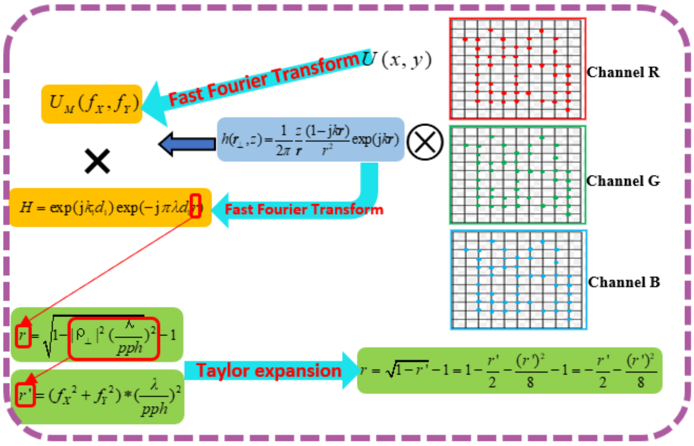

Figure 3. Schematic diagram of the hologram generation stage of TR-PCG.

3. EXPRIMENT AND RESULTS

In this section, the proposed 3D significant object detection model is combined with the point cloud gridding algorithm to generate holograms, and the reconstruction speed and quality are compared with the ROI algorithm. The Kinect 2.0v depth camera is used to collect depth maps and color maps. The simulation test is implemented in MATLAB 2021b and runs on Windows 10 and Ubuntu 22.0 64-bit PCs with RTX3070 unique display (8G video memory) and 12th-generation Core i7-12700H (16 GB memory). The experimental results show that the proposed method is effective. Figure 5 compares the effects of the results produced by the traditional Dilated residual networks (DRN) algorithm, reverse attention and residual net (RAS) algorithm, U^2-Net algorithm, and U^2-RAS algorithm, respectively. The detected object is white and the background part is black. From Figure 4(b), (c), (d), and (e), it is obvious that the RAS algorithm and the U^2-Net algorithm can detect complete objects. The objects detected by the U^2-RAS algorithm are more complete and the effect is more accurate.

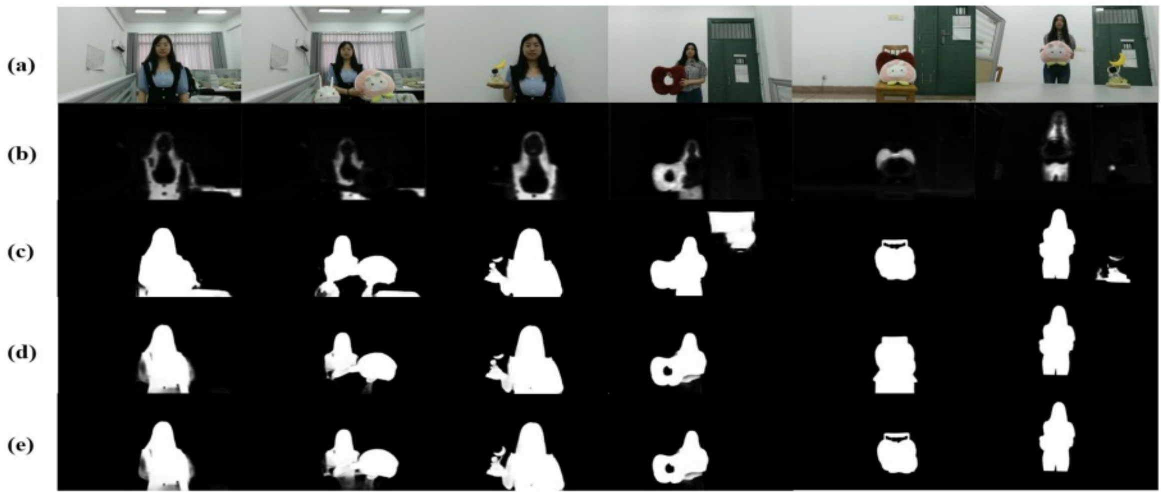

Fig.4. (a)Color image of real objects and their masks generated by (b) DRN, (c)RAS, (d)U^2-Net and (e)U^2-RAS algorithm

Table 1 shows some evaluation metrics: F-measure [17], S-measure [18], E-measure [19] and mean absolute error (MAE) [20].

F-measure comprehensively considers both precision and recall by computing the weighted harmonic mean:

$$F\text{-measure} = \frac{(1+\beta^2)\text{Precision} \times \text{Recall}}{\beta^2\text{Precision+Rcall}}, \quad (21)$$

Empirically, β^2 is set to 0.3 to put more emphasis on precision. S-measure evaluates the structural similarity between the real-valued saliency map and the ground-truth map. It considers object-aware (S_o) and region-aware (S_r) structure similarities:

$$S\text{-meansure} = \alpha \times S_o + (1-\alpha) \times S_r, \quad (22)$$

where α is empirically set to 0.5. E-measure considers global means of the image and local pixel matching simultaneously:

$$E - \text{meansure} = \frac{1}{W \times H} \sum_{i=1}^{W} \sum_{j=1}^{H} \phi_S(i,j), \quad (23)$$

where ϕ_S the enhanced alignment matrix, reflecting the correlation between W and H after subtracting their global means, respectively.

MAE denotes the average per-pixel difference between a predicted saliency map and its ground truth mask. It is defined as:

$$MAE = \frac{1}{W \times H} \sum_{r=1}^{H} \sum_{c=1}^{W} |P(r,c) - G(r,c)|, \quad (24)$$

where P and G are the probability map of the salient object detection and the corresponding ground truth respectively, (H, W) and (r, c) are the (height, width) and the pixel coordinates.

Table 1. Evaluation metrics

	F-measure	S-measure	E-measure	MAE
U^2-RAS	0.419	0.552	0.857	0.153
U^2-NET	0.281	0.456	0.808	0.193
RAS	0.341	0.502	0.738	0.157
DRN	0.295	0.510	0.492	0.128

As shown in Figures 5 (a) and (b), compared with the traditional ROI algorithm, the U^2-RAS algorithm can remove redundant backgrounds more effectively. Figures 5(c) and (d) show the reconstruction images with different focal lengths obtained by using the U^2-RAS algorithm. The experimental results show that clear 3D objects can be reconstructed by using RGB - D salient object detection and point cloud gridding algorithm.

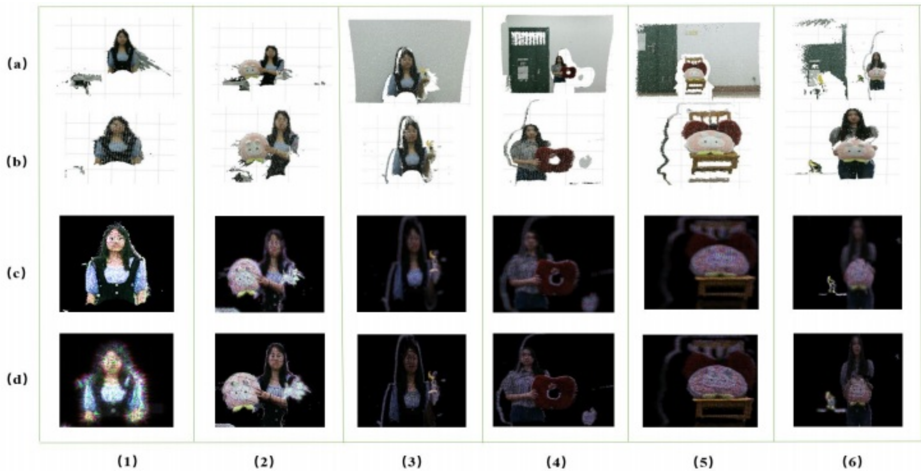

Fig.5. Point cloud map generated by (a)ROI and (b)U^2-RAS algorithm; Reconstruction with focal distance at (c)300 mm and (d)500 mm.

In order to verify the validity of Taylor expansion in the proposed method, we remove Taylor expansion on the basis of TR-PCG and call this method the Rayleigh-Sommerfeld PCG method without Taylor expansion (RS-PCG). In our paper, the proposed TR-PCG algorithm is compared with the WRP, the traditional PCG algorithm and the RS-PCG. The reconstruction quality of several methods is compared by the Peak Signal to Noise Ratio (PSNR) algorithm.

We verify the effectiveness of the proposed method through simulation experiments. The resolutions of the holograms are 1024x1024 and the pixel pitch is 7.4μm. The wavelengths of red, green and blue light source are set to 633nm, 532nm and 473 nm respectively. Table 2 and Table 3 compare the calculation time of WRP, PCG, RS-PCG and TR-PCG algorithms when using CPU and GPU respectively. Compared with the other three algorithms, the TR-PCG method used in this paper improves the computational hologram generation speed by 1.3-12130.3 times using CPU and 1.6-80902.8 times using GPU.

Table 2. Comparison of CPU calculation time of holographic system. Running time is measured in seconds.

Object	WRP	PCG	RS-PCG	TR-PCG
Fig 6.1	29237.31	15.18	10.65	8.09
Fig 6.2	30,926.27	20.07	14.08	10.68
Fig 6.3	148,787.01	29.07	20.79	15.99
Fig 6.4	139,734.11	14.37	10.45	7.54
Fig 6.5	155,510.18	23.52	17.21	12.82
Fig 6.6	29553.82	29.01	21.01	15.77

Table 3. Comparison of GPU calculation time of holographic system. Running time is measured in seconds.

Object	WRP	PCG	RS-PCG	TR-PCG
Fig 6.1	3,559.91	0.30	0.27	0.25
Fig 6.2	4,164.20	0.51	0.50	0.31
Fig 6.3	24,423.68	1.66	1.54	0.99
Fig 6.4	16,898.58	0.36	0.31	0.21
Fig 6.5	26343.36	0.88	0.72	0.75
Fig 6.6	3,145.12	1.05	1.00	0.99

4. CONCLUSION

We proposed a U^2-RAS-based salient object detection method to improve the image accuracy of the holographic system. Compared with the traditional ROI method, DRN, and U^2-net methods, our proposed U^2-RAS network allows a deep architecture with rich multi-scale characteristics to detect objects more accurately and efficiently. Meanwhile, we also proposed a full-color holographic display system based on the Hybrid Taylor Rayleigh-Sommerfeld diffraction algorithm. It is to perform Taylor expansion on the radial value of Rayleigh-Sommerfeld diffraction in the hologram generation stage and modify the data type to effectively accelerate the calculation speed and ensure the reconstruction quality. Compared with the wave-front recording plane (WRP), traditional point cloud gridding (PCG), and Rayleigh-Sommerfeld PCG without Taylor expansion, the computational complexity is significantly reduced. This will promote the development of CGH generation and full-color holographic reconstruction technology and reduce the consumption of hardware resources.

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Wide field of view high-resolution digital holographic microscope using digital micromirror device

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ABSTRACT

Digital holographic microscopy (DHM) simultaneously acquires the phase as well as the amplitude of an object wave and it is useful to measure an object precisely throughout the industry. In DHM, as in general microscopes, the numerical aperture (NA) that determines resolving power is an important factor. But NA is limited by the objective lens, so synthetic aperture (SA) has been proposed to overcome this. The SA implements a single high-resolution image by synthesizing multiple high-frequency images in the Fourier domain. In order to apply SA in DHM, a system needs to control the direction of the object beam. In this paper, a beam steering optical system suitable for SA-DHM is designed and its feasibility is verified.

Keywords: Holography, Microscopy, Synthetic aperture

1. INTRODUCTION

Digital holographic microscopy (DHM) is an advanced technique to acquire both amplitude and phase of a microscopic object. The DHM captures interference pattern of microscopic objects and removes twin noise and DC components to extract only the complex information of objects. In general, high NA objectives are used to achieve high resolution in DHM. An optical system with a high NA captures a wide range of divergence angles, ensuring high spatial resolution. However, due to the spatial bandwidth product (SBP) of optics, there is a trade-off between spatial resolution and the measurable field of view (FOV). To overcome this problem, the synthetic aperture (SA) method has been proposed [1]. The SA method acquires high-frequency images of the sample and combines them in the Fourier domain to expand the Fourier spectrum. The extended Fourier spectrum is filled with high frequency components and the resultant image has high spatial resolution. To apply the SA, a system needs to acquire multiple spatially different images. One common approach is to rotate the sample mount itself. By rotating the sample in a specific direction while illuminating it from a specific angle, spatially different images of the sample is obtained [2]. Another approach is to control the angle of the illumination. It is practically difficult to control a laser beam with high coherence by making it into an individual module like ptychography [3]. So, an optical system using a Galvano mirror has been proposed to control the direction of laser beam [4, 5]. The beam is deflected in the x-axis and y-axis directions reflected by Galvano mirrors, and the beam passes through a condenser lens to illuminate the sample with a wide illumination angle. But these methods suffer from instability issues caused by the vibrations associated with physically control such as motors.

In this paper, we design a beam steering optical system suitable for the SA applied DHM and experimentally validated its feasibility. The proposed method is based on a digital micro-mirror device (DMD). The DMD allows fast and flexible control of the laser light source and, most importantly, benefits from precise modulation at the individual micromirror level [6]. So, by partially and selectively turning on and off the micromirrors of the DMD, the direction of the beam is controlled and high-frequency images of the sample are acquired. Subsequently, the high-frequency images are overlapped and aligned in the Fourier domain, and the resultant Fourier spectrum is expanded. Finally, the synthetic aperture Fourier spectrum is restored to validate the potential for high-resolution sample measurements.

2. EXPERIMENTAL METHOD

The overall schematic diagram of the proposed SA-DHM optics is depicted in Figure 1. A fiber-type laser with a wavelength of 532nm is used as the light source. The beam from the light source is split into the object arm and the reference arm through a fiber beam splitter. In the reference arm, the collimator transforms the beam into a plane wave with an increased size of diameter, which is then captured by the sensor after a beam splitter. Similarly, in the object arm, the beam also passes through a collimator to increase its size. The beam then enters the DMD through a total internal reflection prism. The modulated beam from the DMD passes through a 4*f* optics and subsequently through a micro-lens array.

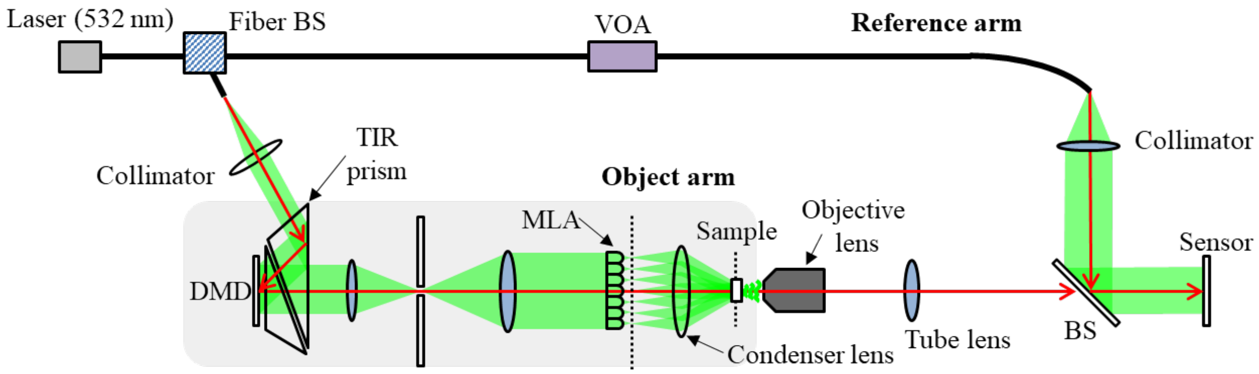


Fig.1. The schematic of the proposed SA-DHM

The beams after the MLA passes through a high NA condenser lens and it illuminates the sample surface at a specific oblique angle. Illumination light is scattered and diffracted by the sample, and these beams are focused on the sensor through an objective lens and a tube lens. On the sensor, the image of the object plane magnified by the objective lens interferes with the reference wave.

2.1 Beam steering optics with DMD

The proposed SA-DHM illuminates the beam in a desired direction on the sample plane by controlling the position of micromirrors on the DMD. Figure 2 shows the schematic diagram of the beam steering optics in the proposed SA-DHM system.

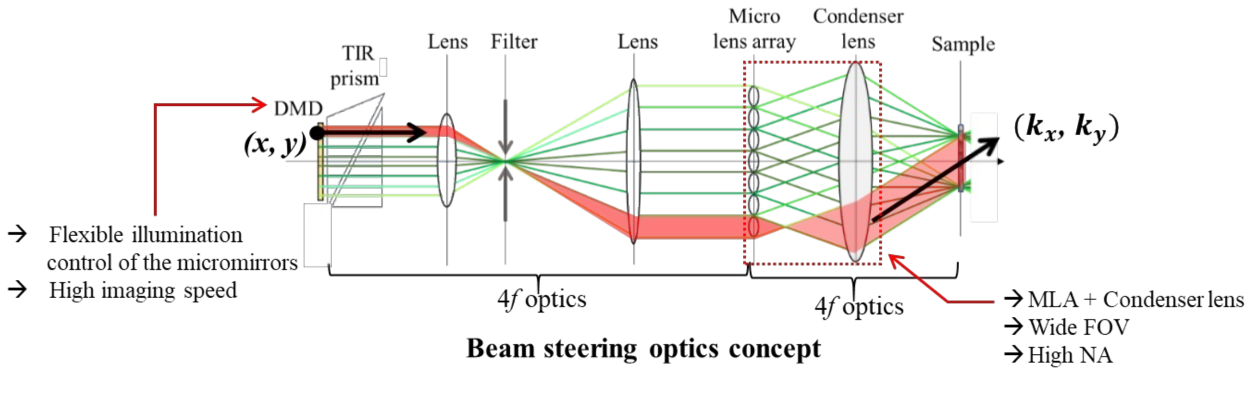
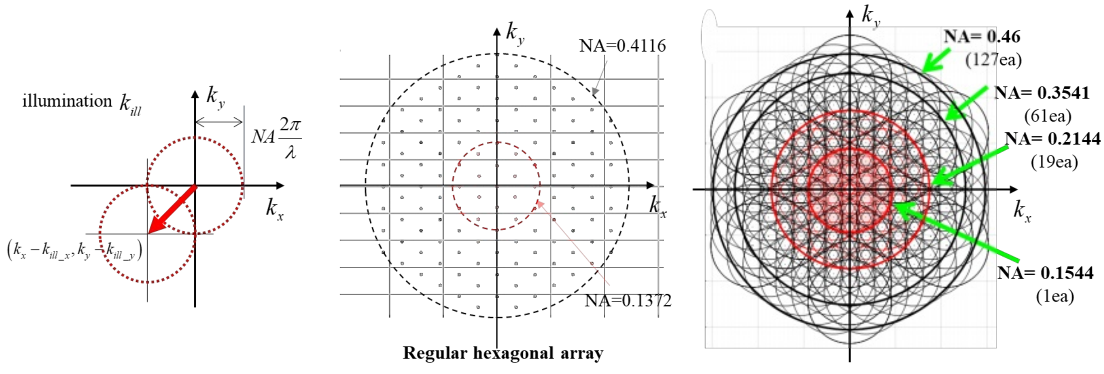


Fig. 2. Schematic of the beam steering optics with DMD and MLA

A plane wave is brought into the DMD by a collimator. When a circular aperture area centered at a specific position (x, y) on the DMD is turned on, a parallel beam with a circular shape centered at position (x, y) is emitted. At the same time, higher-order diffraction signals are also generated by the DMD. These diffraction signals are filtered by the iris of the 4*f* optics. The 4*f* optics causes only parallel light corresponding to dc of the DMD to enter the MLA, and the circular aperture at a specific position (x, y) of the DMD is matched. Each lens of MLA and condenser lens are regarded as 4*f* optics. So, the beam entering the lens of MLA is converged by the focal length of the lens and diverged again by the back focal length of the condenser lens. When this beam passes through the condenser lens, it finally becomes parallel light that is irradiated onto the sample surface at an oblique angle. As can be seen from the optical structure of Figure 2, the k-vector (k_x, k_y) of the illumination directed to the sample surface is determined by the position (x, y) in the DMD. A high angle of illumination is formed from the light at the edge of the DMD. In addition, the diameter of the beam directed to the sample surface increases by the ratio of the focal lengths of the MLA and the condenser lens, so there is an advantage that the FOV, that is the diameter of the illumination beam is large enough.

2.2 Synthetic aperture Fourier spectrum of complex data

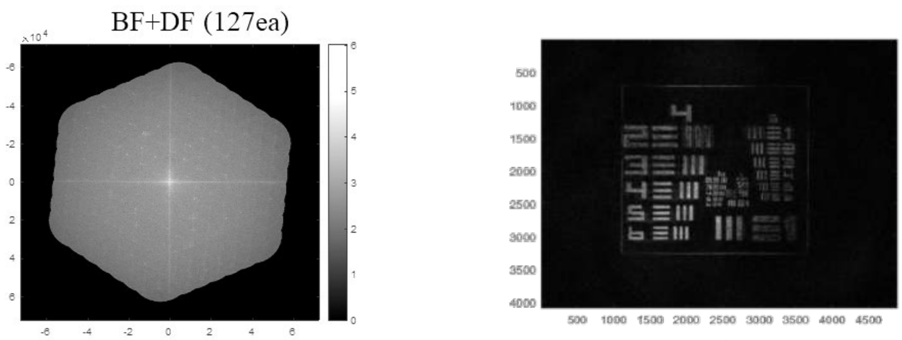


(a) (b) (c)

Fig. 3. (a) Fourier spectrum of objective lens (b) Positions of the k-vector of the illuminations (c) Expended Fourier spectrum by the Synthetic aperture in the proposed SA-DHM

Through beam steering optics, a beam controlled in a specific direction illuminates the sample. The illuminated beam is scattered and diffracted by the sample and interferes with the reference wave. In order to use the SA method, frequency information in the Fourier domain needs to be analyzed. By separating twin and dc noise through off-axis interference, the complex data of the sample can be obtained. The acquired data is a circular Fourier spectrum, as shown in Figure 3(a). The obtained Fourier spectrum is shifted according to the k-vector of the corresponding illumination. In the proposed Beam steering optics, a total of 127 different frequency images are obtained for different illumination k-vectors. Figure 3(b) shows the locations of the 127 different k-vectors on the k-vector diagram. The Fourier spectrum is extended by moving the corresponding Fourier spectrum around the position of the k-vector. Finally, as shown in Fig. 3(c), it can be seen that the high-frequency signal of the Fourier spectrum is increased by SA. When all 127 Fourier spectrums are used, the NA is 0.46, which is about 3 times higher than when only one spectrum is used.

3. EXPERIMENTAL RESULT



(a) (b)

Fig. 4. (a) Fourier spectrums of the proposed SA-DHM (b) Reconstruction results of the Synthetic aperture Fourier spectrums

The images obtained through the proposed SA-DHM experimental setup are synthesized with a synthetic aperture, and reconstruction is performed. The sample used in the experiment is a USAF target, and Fig. 4(a) shows the progress of the extended Fourier spectrum. It is obvious that the Fourier spectrum combining 127 significantly increases the high-frequency component. In addition, it is confirmed that the frequency components of the USAF target, which appear mainly in the horizontal and vertical directions in the Fourier domain, are well represented as the images are synthesized. Figure 3(b) is the result of reconstruction of Figure 3(a) to the object domain. As a result of the reconstruction, it can be seen that the USAF target comes out clearly. For high-resolution measurement analysis, the work shown in Fig. 5 is carried out.

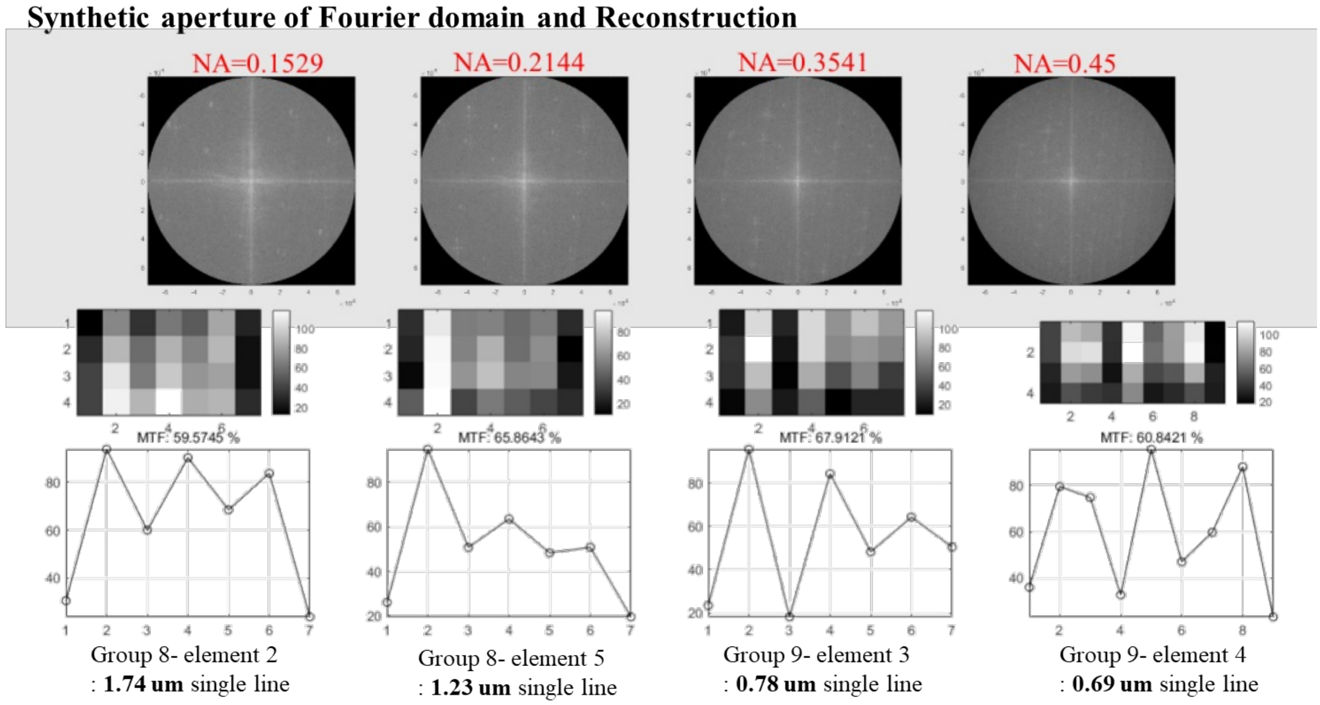


Fig. 5. Analysis of high-resolution line-pair of the reconstruction results

Figure 5 is the result of analyzing the reconstruction according to the diffraction limit by masking by 4 different NAs. The NAs are 0.1529, 0.2144, 0.3541 and 0.45, and the minimum line-pair of USAF that is distinguishable from the corresponding NA is shown in the graph above. The MTF of the line pair appears as a result of almost 60%, and it can be seen that the line also occupies about 1 pixel according to the diffraction limit. When the NA is 0.45, the result of occupying 2 pixels per 1-line pair is obtained, which is expected to produce more accurate results when noise filtering is performed later.

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Calculation technique for large backdrops filing visual field of full-parallax high-definition CGH

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ABSTRACT

A fast method is proposed to compute large background wavefields in full-parallax high-definition computer-generated holograms (FPHD-CGH) to fill the 3D scene with light or images. The proposed method uses single-step Fresnel propagation (SSFP) to increase the size of the background field without increasing computational costs. The SSFP features sampling intervals of a wavefield change before and after propagation. An FPHD-CGH calculated using the proposed methods is fabricated and demonstrated to verify the validity of the method.
Keywords: Large-scale CGH, full-parallax CGH, backdrop

1. INTRODUCTION

The computer-generated hologram (CGH) has a long history over 50 years. However, it was just 14 years ago that large-scale full-parallax CGHs, comparable to traditional analog holograms, were created in practice [1]. The large-scale CGHs, sometimes referred to as full-parallax high-definition CGHs (FPHD-CGH), reconstruct very impressive deep 3D images. However, creation of the FPHD-CGHs has a severe problem, called the space-bandwidth product problem; the viewing angle of a CGH increases almost inverse proportionally to pixel pitches of the fringe pattern, while the size of a CGH is given by the product of pixel pitches and the number of pixels. Therefore, a CGH having both a large size and viewing angle needs large-scale display resolution. For example, when the pixel pitch is 0.8 μm, the viewing angle is approximately 45° in red color. Therefore, when we create a CGH whose size is 5×5 cm^2, the required number of pixels is over four billion pix. This is almost two thousand times larger than that in a full HDTV. As a result, much computational effort is required to calculate an FPHD-CGH. However, recent developments of computer technology and algorithms for calculating CGHs make it possible very large-scale FPHD-CGHs, whose resolution is over 100 billion [2].

The FPHD-CGHs can reconstruct amazing deep 3D scenes with natural depth cues. On the other hand, it is still difficult to calculate CGHs that reconstruct 3D scenes whose field of view is filled with light or images, like ordinary landscape paintings and photographs. It is only possible in current computer holography to reconstruct 3D scenes floating in outer space, i.e., in the black background, as shown in Fig. 1. This is because the backdrop, which covers the whole field of view of the 3D scene, must have very large physical size in high-definition computer holography. As a result, calculation of such large background wavefields requires very large computer resources and long computation time. We propose a fast method to compute large-scale background wavefields in FPHD-CGHs to fill the 3D scene with light or images. This method uses single-step Fresnel propagation (SSFP) that requires fast Fourier transform (FFT) only once [3, 4]. In the numerical calculation, the size of the sampling window at the destination plane changes from that at the source plane without changing the sampling number. The destination and source window sizes depend on several parameters.

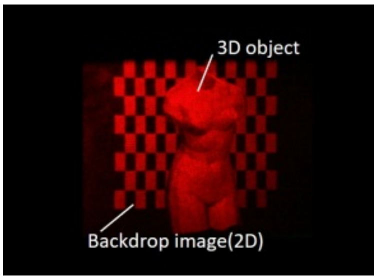

Figure 1. The optical reconstruction of the conventional FPHD-CGH [1]. The reconstructed 3D object seems to be floating in outer space.

In this study, we control the size of the sampling windows before and after numerical propagation to realize large background wavefields without increasing computational costs. Moreover, we propose a technique of hidden surface removal (occlusion processing) in the proposed method because the silhouette method [5], which is usually used for occlusion processing in FPHD-CGHs, cannot be applied in this case. An actual FPHD-CGH was calculated using the proposed method and demonstrated to verify the validity of the method.

2. PRINCIPLE FOR GENERATING LARGE BACKDROP WAVEFIELD

To generate large backdrop wavefields, we use SSFP which is one of the most well-known numerical techniques to calculate optical diffraction under Fresnel approximation.

2.1 Characteristics of single-step Fresnel propagation (SSFP)

Figure 2 shows the coordinate system used in SSFP. Propagated wavefield $f(x, y; d)$ in the destination plane is calculated from the source field $f(x_s, y_s; 0)$ as follows:

$$\begin{aligned} f(x,y;d) &= A(x,y;d)\iint f(x_s,y_s;0)\exp\left[i\frac{\pi}{\lambda d}(x_s^2+y_s^2)\right]\times\exp[-i2\pi(u_s x_s+v_s y_s)]dx_s dy_s \\ &= A(x,y;d)\times \mathrm{F}\left\{f(x_s,y_s;0)\exp\left[i\frac{\pi}{\lambda d}\left(x_s^2+y_s^2\right)\right]\right\}_{u_s=\frac{x}{\lambda d},\ v_s=\frac{y}{\lambda d}} \\ A(x,y;d) &= \frac{\exp(ikd)}{i\lambda d}\exp\left[i\frac{\pi}{\lambda d}(x^2+y^2)\right], \end{aligned} \tag{1}$$

where λ and *d* is a wavelength and propagation distance, respectively. $\mathrm{F}\{\cdot\}$ stands for Fourier transform, where

$$u_s = \frac{x}{\lambda d}, \quad \text{and} \quad v_s = \frac{y}{\lambda d}, \tag{2}$$

are Fourier frequencies of the source field in the x_s and y_s direction, respectively. Here, note that *x* and *y* denote the destination coordinates.

When FFT is used for the Fourier transform in Eq. (1), sampling intervals in the Fourier space are given by $\Delta u_s = (M\Delta x_s)^{-1}$ and $\Delta v_s = (N\Delta y_s)^{-1}$, where *M* and *N* are the numbers of samplings, and Δx_s and Δy_s are sampling intervals of the source field. Using Eq. (2), because $\Delta x = \lambda d \Delta u_s$ and $\Delta y = \lambda d \Delta v_s$, sampling intervals of the destination field are given by

$$\Delta x = \frac{\lambda}{M\Delta x_s}d \quad \text{and} \quad \Delta y = \frac{\lambda}{N\Delta y_s}d\,. \tag{3}$$

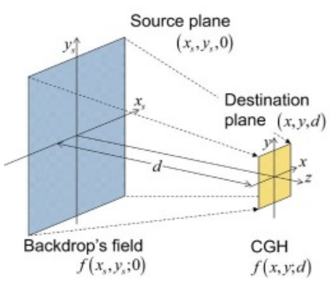

Figure 2. The arrangement of a large backdrop in the 3D scene, and the coordinate systems and symbols used for formulation.

2.2 Control of sampling window size

SSFP has an advantage that Fresnel propagation can be calculated only by a single FFT. However, in this technique, the sampling intervals are always proportional to the propagation distance. This is commonly a disadvantage in calculating CGHs. However, some propagation techniques, such as the multi-step Fresnel method [6] and shifted Fresnel method [7], utilize SSFP to control the sampling interval. We also use the characteristics of SSFP to calculate the wavefield of a backdrop, whose size is much larger than the CGH, as shown in Fig.2. If we use the angular spectrum method (ASM) based on fast convolution by a double FFT for the numerical propagation of the backdrop's wavefield, the number of samplings of the backdrop's wavefield is most likely gigantic number. This is because the backdrop's wavefield must have the same high sampling density as that of the CGH and the sampling interval does not change before and after propagation in ASM.

Unlike ASM, the sizes of the source sampling window in SSFP are not constant, and given by Eq. (3) as follows,

$$W_{sx} = M\Delta x_s = \frac{\lambda}{\Delta x} d \quad \text{and} \quad W_{sy} = N\Delta y_s = \frac{\lambda}{\Delta y} d \; . \tag{4}$$

Therefore, the source sampling window expands proportionally to the propagation distance d. Figure 3 shows the example of the size of source sampling window W_{sx} in the x direction as a function of d. Here, we used parameters: λ = 633 [nm], Δx = 0.8 [μm], and M = 131,072. The ratio of W_{sx} to d is given by $\lambda/\Delta x$ and approximately 0.8 in this case.

We chose d = 500 [mm] in the fabricated CGH to enlarge the size of the backdrop fields roughly 4 times larger than that of the CGH.

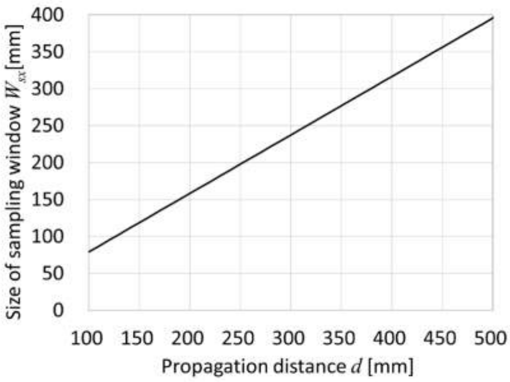

Figure 3. The actual example of the size of the source sampling windows as a function of propagation distance d.

3. FABRICATION OF AN FPHD-CGH USING THE PROPOSED METHOD

We fabricated an FPHD-CGH to demonstrate that FPHD-CGHs with a large-scale backdrop can be calculated with proper occlusion processing using the proposed method.

3.1 Parameter of the fabricated FPHD-CGH

Figure 4 and Table 1 show the 3D scene and the parameters of the FPHD-CGH, respectively. The 3D scene consists of a backdrop and an object. The backdrop is a picture of Mt. Fuji, whose width and height are 400 mm. The propagation distance d of SSFP is given by the distance between the backdrop and hologram and is 500 mm in this CGH, as mentioned in the previous section. In addition, we arranged maple branches at 80 mm behind the hologram. Note that the horizontal pixel pitch is 0.8 μm, while the vertical pitch is 0.4 μm in order to avoid non-diffraction and conjugate light using the fringe-oversampling technique [8].

3.2 Procedure for occlusion processing

In the proposed method, the wavefield of the backdrop is directly propagated to the hologram plane. Thus, the ordinary silhouette method, where the field is calculated from the furthest plane to the hologram in order of the distance from the hologram, cannot be used for occlusion processing. Therefore, we devised a procedure shown in Fig.5 to calculate the wavefield of the 3D scene with proper occlusion processing.

The generated backdrop's wavefield whose sampling intervals Δx_s and Δy_s are given by Eq. (3) is first propagated to the hologram plane using SSFP. Then, the destination sampling window of SSFP is expanded by zero padding so as to cover the whole diffraction area of the object. After that, the backdrop's wavefield is propagated back to the object plane that slices the object as in Fig.4 using ASM. In the object plane, a part of the backdrop's wavefield, which is shielded by the object, is removed by the silhouette mask [5]. Then, the object wavefield is added to the shielded backdrop's wavefield. Finally, the resultant wavefield is propagated to the hologram plane again and trimmed to fit the wavefield with the hologram.

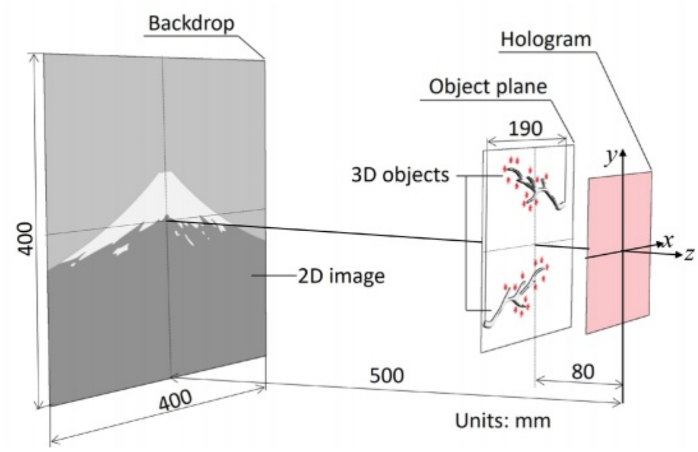

Figure 4. The 3D scene of the fabricated FPHD-CGH.

Table 1. The parameters of the fabricated FPHD-CGH.

Hologram	
Number of pixels	131,072 × 262,144
Pixel pitches	0.8 μm × 0.4 μm
Wavelength	633 nm
Backdrop's wavefield	
Number of samplings	131,072 × 131,072
Sampling intervals	3.0 μm × 3.0 μm

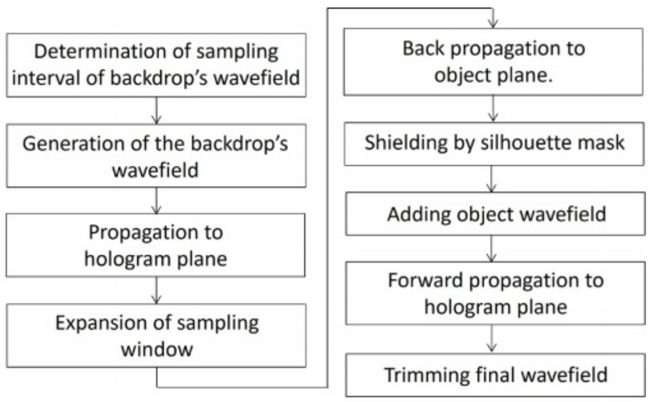

Figure 5. The proposed procedure to calculate the wavefield of the 3D scene with occlusion processing.

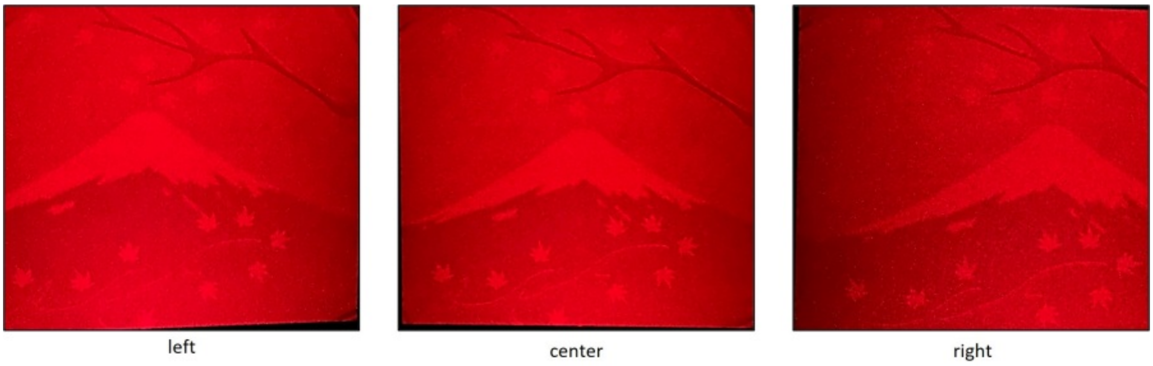

Figure 6. Optical reconstruction of the fabricated FPHD-CGH.

3.3 Optical reconstruction of the fabricated FPHD-CGH

Figure 6 shows photographs of optical reconstruction of the fabricated FPHD-CGH. The photographs are taken from different viewpoints. We can confirm that the backdrop fills the whole visual field when seeing from any viewpoint. Moreover, occlusion between the backdrop and maple branches is correctly processed by the proposed procedure.

4. CONCLUSION

We have proposed a new technique to calculate the large-scale wavefield of a backdrop without increasing computational burden. We make use of the fact that the size of the sampling window changes proportionally to the propagation distance in SSFP. The proposed technique has an additional advantage that the SSFP is faster than other propagation techniques because it requires only a single FFT. Therefore, the proposed method is suited for creating very large-scale FPHD-CGHs. An FPHD-CGH, fabricated to confirm the validity of the proposed technique, shows that the large backdrop image covers the whole of the visual field in the optical reconstruction. Our future research is to apply the method to full-color FPHD-CGHs.

ACKNOWLEDGEMENT

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Fabrication method of holographic optical element (HOE) based on distortion-free reflective imaging system

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ABSTRACT

In this paper, we focus on experimental analysis on the imaging characteristics of holographic optical element (HOE) lens which was fabricated by two spherical waves. An analytical approach for correcting a distortion of the holographic projection display incorporating HOE has been implemented. The proposed method utilizes HOE as a see-through reflective screen for the holographic projected image and HOE combiner is fabricated under various experimental conditions to analyses a distortion and imaging quality of holographic projected image for compact Near-eye display (NED). Our display system consists of two parts: holographic projection display which utilizes phase-only spatial light modulator (SLM) as a micro display and HOE as holographic lens which has the advantages of low manufacturing cost and suitable for realizing three-dimensional reconstruction of arbitrary wavefront of any object. We recorded single-shot HOE at the diverging and converging signal wave conditions separately and analyzed display effect of image quality and eye-box size of each case. Since the distortion is the aspect of the optical setup, it can be corrected by adjusting the mismatch of the optical component properly with the help of numerical calibration algorithm. The experimental results prove that our system is simple and effective to achieve the distortion-free reconstruction of holographic 3D object and it has better quality performance.

Keywords: Times Roman, image area, acronyms, references

1. INTRODUCTION

Holographic optical element (HOE) is one kind of diffractive optical element (DOF) based on holographic technique and it has optically see-through characteristics due to their higher angular and wavelength selectivity. Based on these properties, several AR display systems have adopted HOEs as an image combiner or see-through screen. Therefore, it has many advantages of light weight, compact form factor, low manufacturing cost and optically see-through properties due to their high angular and wavelength selectivity. HOEs can record various optical functions such as lenses, mirrors, and diffusers in single thin film. HOE's have been employed in various fields such as in AR-NEDs [1-2], HOE combiner [3], and dynamic holographic display [4]. Holographic display reconstructs the wavefront of the desired three-dimensional (3D) images by modulating the complex amplitude distribution using a spatial light modulator (SLM). The main drawback of typical holographic display is a limited space-bandwidth product (SBP) and a small projection angle which results from fixed display resolution and pixel pitch. A small diffraction angle results in a small visual angle. Therefore, there is a trade-off between the display size and the visual angle. Authors in [5] report a projection-type holographic 3D display with a high degree of freedom of the display size and visual angle based on the combination of digital holographic projection and digitally designed HOE called DDHOE. Holographic projection display has the severe image distortions of 3D space owing to the mismatch between the axial and lateral dimensions caused by the enlarged projection, and the image distortion due to observation of the hologram screen from an oblique direction [6]. Distortion is a kind of aberration that affects the image quality of holographically reconstructed images. It is mainly caused by the manufacture defect of optical elements and the misalignment of optical components of SLM lens system. Also, part of it comes from the fabrication process of HOE [7]. Distortions can be corrected by using precision optics, but it is costly and time consuming. Authors in [8] recently addressed the image quality of a holographic lens with a non-converging signal wave for compact near-eye displays. As mentioned in reference, if one fabricates the holographic lenses (HLs) by using converging signal waves, the NEDs suffer from the tiny eye-box (approximately 1 mm) corresponding to the focal size of the HLs. On the other hand, diverging signal waves allow the HLs to have an affordable sized eye-box to enable practical NEDs. In contrast to the converging signal wave based HLs, unfortunately, light rays emitted from most pixels of an image source deviate from the Bragg condition of the HLs. Since aberrations arising from the inherent off-Bragg diffraction tend to degrade the quality of virtual images, design parameters required in a recording and playback geometry should be carefully analyzed to overcome these artifacts. Our work is inspired by KETI [8], and we suggest another analysis model based on not only diverging signal wave but also converging signal wave condition and compare them in terms of distortion effect and diffraction efficiency. In section 2, we will present our previous work on lens-array HOE fabrication and current work on holographic projection display based on HOE for compact augmented reality near-eye display AR-NED.

2. PRINCIPLE

2.1 Previous work: Fabrication of lens-array HOE

Holographic optical elements have optically see-through properties due to their high angular selectivity, which has an extensive potential to be employed as an image combiner for the AR based devices. According to the designed functions, HOEs can be categorized into several types such as lens, mirror, and diffuser HOEs. In our previous work, we fabricated lens-array HOE using our prototype holographic printer system. Holographic printers have the potential to realize complex optical functions of conventional lens-array with high diffraction efficiency while maintaining excellent transmittance for see-through 3D display. Figure 1 shows the typical implementation of lens-array HOE fabrication process.

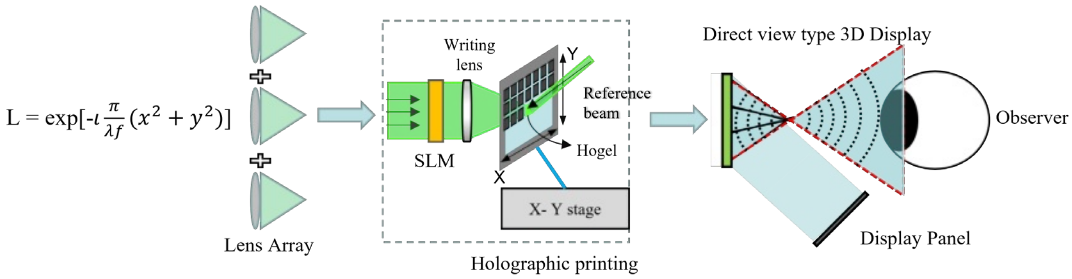


Figure 1. The schematic configuration of lens-array HOE fabrication.

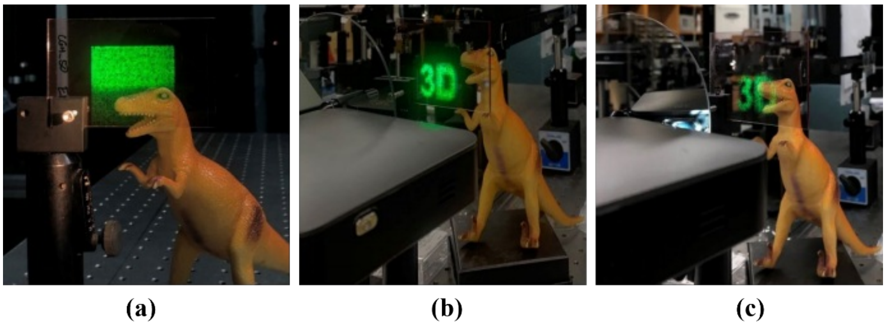


Figure 2. Example of reconstructed images: (a) fabricated lens-array function, (b) left view, (c) right view.

Not only holographic printer can record a hologram of 3D images, but also it can manufacture an HOE by recording a complex pattern of digitally designed optical element. Once we obtain the complex field of the designed lens array by simple computational configuration as shown in Fig. 1, it needs to segment this complex field to match with the structure of hogel matrix. The divided sub segments will represent the entire complex field of LA. Repeating this recording procedure for all the hogels will implement the printed HOE LA with the designed specifications. Figure 2 presents some examples of reconstructed images. The elemental image is projected to the fabricated lens-array HOE and integrated as 3D image according to the principle of Integral imaging technique. However, the image quality was not good enough and lens distortion was introduced to the observed images. This work was extended to projection-type holographic display based on HOE to achieve aberration or distortion free imaging system. This process will be introduced in the following section 2.2 in detail. Table 1 shows some specifications of printed LA-HOE by holographic printer and optimized parameters for better image quality performance.

Table 1. Specifications of printing lens-array HOE.

Parameter	Value	Parameter	Value
Number of hogels	50 × 50	Exposure time	2 second
Resolution of a hogel	1000 × 1000 pixels	Exposure energy/hogel	~ 5mW/cm2 (1:1 ratio)
Total resolution of the HOE	50,000 × 50,000 pixels	Size of a hogel	1 mm × 1 mm
Focal length of the HOE	30 mm	FOV of the HOE	30 degrees
Recording wavelength	532 nm	LA pitch and focal length	1 mm and 3.3 mm

2.2 Holographic projection display incorporating HOE.

In holographic projection display combined with AR system, the displayed computer-generated hologram (CGH) is directly projected onto the HOE combiner to reconstruct the virtual image mixed with the real object. The HOE acts as a forward scattering screen for the projected holographic images. Due to the angular and wavelength selectivity of the HOE, the optical combiner only diffracts the light from the micro display, while allowing the light coming from the real environment to pass through unaffected based on Bragg condition. The image source can be a conventional 2D display or a 3D image source such as a digital holographic display using a spatial light modulator (SLM) and laser light source. The main function of HOE is to reconstruct the desired wavefront at the designed distance. HOE is an off-axis reflective diffractive optical element which is recorded by holographic interference principle. In Figure 3, our display system is mainly composed of two parts: SLM projection module with laser illumination and holographic combiner. In a typical implementation of HOE based NEDs, the rays from an image source propagate in the free-space and arrive at the observer's eye after diffraction by fabricated HOE-lens.

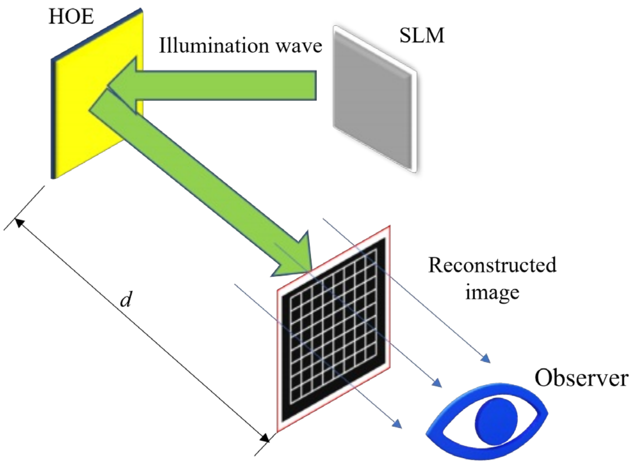


Figure 3. The schematic of holographic projection display based on HOE.

During recording, the object light wave modulated by the SLM is equivalent to spherical light waves. We assume that the HOE is fabricated by two diverging/converging spherical waves. SLM is used to load the phase distribution. In long-distance projection, one has the freedom of choosing the scheme of illumination of the SLM. Generally, the FOV or maximum diffraction angle can be calculated as below:

$$\theta = 2\sin^{-1}\left(\frac{\lambda}{2p}\right) \quad (1)$$

Where λ is the wavelength and p is the pixel pitch of SLM. Under the condition that a plane wave illuminates the hologram displayed on SLM, the theoretical minimal projection distances of an SLM with a pixel pitch of p and aperture of D is given by:

$$z = \frac{D}{2\tan\left(\arcsin\frac{\lambda}{2p}\right)} \quad (2)$$

The diffraction of the free space between the HOE and the virtual image is calculated based on Kirchhoff's diffraction integral formula as below:

$$O(x,y) = K\iint A(m,n)\frac{\exp(jkr)}{r}dmdn \quad (3)$$

Where m and n are the coordinates of the diffractive aperture plane, K is the complex constant, k is the wave vector and r are the distance from the target point to the center of the spherical wave. According to the theory of holographic wavefront reconstruction, when the converging signal wave and plane reference beam is used to exposure holographic file from different direction, the converging spherical wave can be reconstructed by irradiating the reference beam on the recording holographic film, which achieves the function of focusing mirror. However, if HOE is fabricated by using converging signal wave, the near-eye display suffers from tiny eye-box size corresponding to the focal size of the HOE. On the other hand, diverging signal waves allow the HOE to have an acceptable eye-box size and larger diffraction angle. We experimentally evaluate display effect and optimize parameters of each case separately. Figure 4 shows an experimental setup for fabricating HOE using converging and diverging signal wave condition. In both cases, the spherical divergence reference wave is used. The reflection-type HOE was fabricated using optical interference between two spherical waves. In Fig. 4(a), the standard focal lens (FL1) with the focal length of 85 mm was used to generate the spherical divergence wave as the signal beam. The reference wave emitted from focal lens (FL2) is a spherical divergence beam with a focal length of 55 mm. In Fig. 4(b), we used long focal length (700mm) lens to generate converging signal waves.

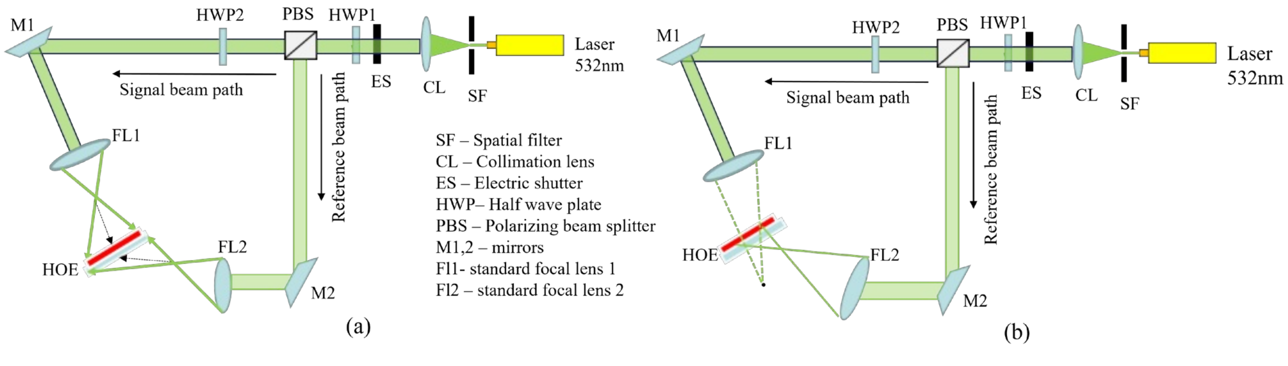


Figure 4. The experimental setups for fabricating HOEs using two spherical waves: (a) Diverging signal wave, (b) Converging signal wave.

The incident angle of reference wave and signal wave is same as 30 degrees to satisfy the symmetric structure. In our previous work [9], we experimentally proved that when the grating recorded at the symmetric structure provides better image quality than the asymmetric structures. We used holographic material as Liti Holo photopolymer.

3. EXPERIMENTAL RESULT

We fabricated two kinds of HOEs based on converging signal wave and diverging signal wave conditions to compare the display result and optimize the recording parameters. Figure 5 and 6 shows the photographs of experimental environment for fabricating HOEs using two different signal wave condition. In the reconstruction process, the recorded HOE can modulate projected holographic image into designed direction. The SLM is arranged in the system to modulate CGH which was calculated by Iterative Fourier Transform Algorithm (IFTA) to generate phase-only hologram. The reference wave illuminates the SLM via beam splitter and then the wavefront information from the SLM is introduced into the 4F optical system. The rectangular filter is inserted in the 4F optical system to pass only first-order diffraction beam.

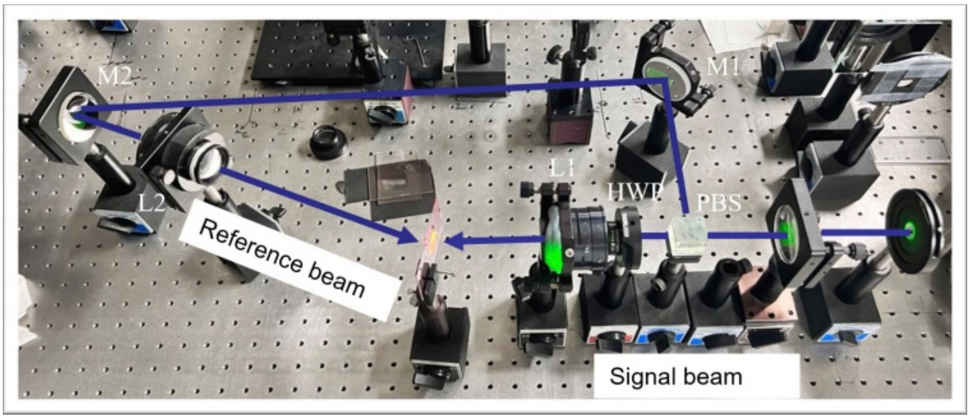


Figure 5. The experimental setup for fabricating HOE using diverging signal wave.

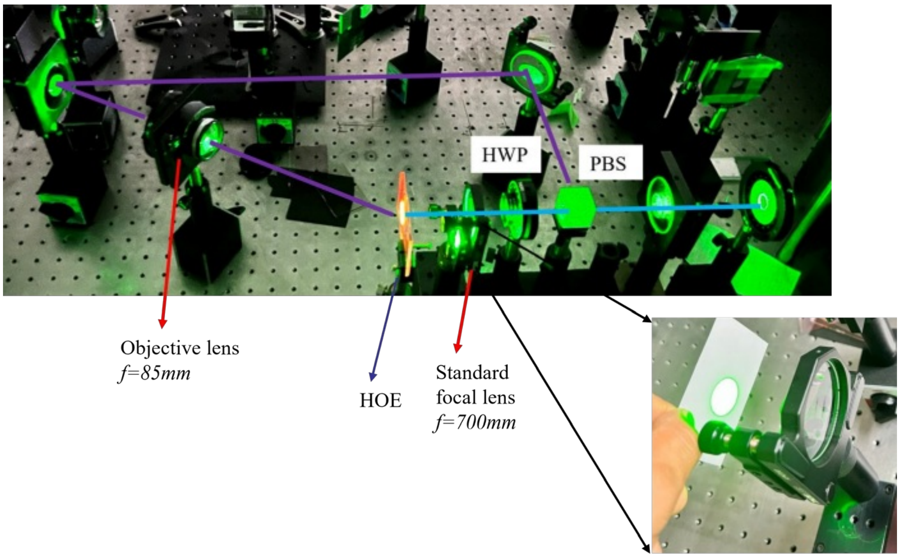
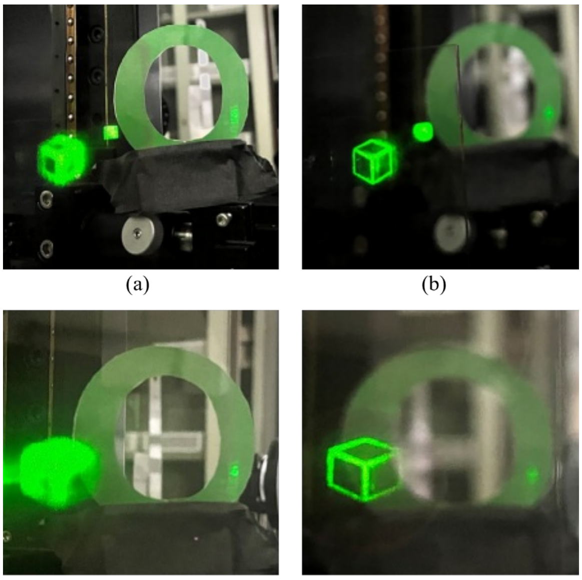


Figure 6. The experimental setup for fabricating HOE using converging signal wave.

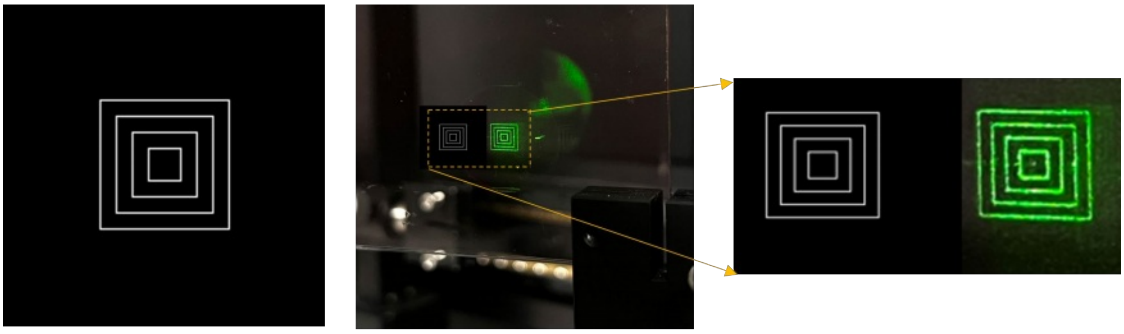
We conducted an experiment for displaying holographic images onto the phase only SLM as micro display. Figure 7 shows the observed images of the prototype system where the virtual image "Cube" was clearly overlapped on the background object and has higher transparency. As shown in Fig. 7(a), observed image by using converging signal wave has tiny eye-box size (approximately 1 ~ 1.5 mm). When eye moves slightly, the reconstructed image disappears and hard to observe within the range. But the diverging signal waves provides reasonable eye-box size as shown in Fig. 7(b). Unfortunately, during the experiment we observed some distorted images called astigmatism aberration due to the mismatch of the Bragg condition. Therefore, it tends to degrade the quality of virtual images. After the many attempts and optimizing optical components, we captured less aberration image as shown in Fig. 7(b).



(a) (b) (c) (d)

Figure 7. Observed images: Converging signal wave (a) focused on background (b) focused on image plane; Diverging signal wave (c) focused on background (d) focused on image plane.

For further investigation for the effect of the distortion, we compared the original image with the reconstructed image. In the Fourier type holographic display, the spatial spectral bandwidth is in inverse proportion to the pixel pitch of the SLM. Thus, in a normal case, the size of viewing window of reconstructed hologram should be the same in horizontal and vertical directions. We tried to reconstruct a holographic image the same size as original image to compare the distortion effect of observed image. Our holographic projection system provides distortion-free image as shown in Fig. 8. In Figure 8, we can observe that the pixel pitch of the SLM image is not stretched after being projected onto HOE.



(a) (b)

Figure 8. Distortion test: (a) original image, (b) observed image with the same size.

4. CONCLUSION

An analytical approach for correcting a distortion of the holographic projection display incorporating HOE and SLM has been proposed. The proposed method utilizes HOE as a see-through combiner for the holographic projection display and HOE lens is fabricated under various experimental conditions to investigate the distortion effect and imaging quality of holographic projected image for compact Near-eye display (NED). We recorded HOE according to the designed parameters at the diverging and converging signal wave conditions separately and analyzed display effect of each case.

In near future, we will extend our work to extend the eye-box by adopting diffuser to increase diffusing angle of diffracted beam.

ACKNOWLEDGEMENT

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Qualified single-image depth estimation-based content generation for full-color holographic printing system

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ABSTRACT

In this paper, qualified single-image depth estimation-based content generation for full-color holographic printing system is proposed. In order to print high-quality three-dimensional (3D) visualization by minimizing the information loss of the original 3D object, digital content generation should be considered before the hardware system of holographic printing is executed. There are two main parts related to digital content generation; 1) acquisition of the 3D point cloud object of the 3D scene is implemented. Here, the depth estimation method is used to generate qualified depth data from a single-shot image, and a 3D model is generated by combining the estimated high-quality depth data and 2D image, then 2) the array of sub-holograms (hogels) is generated within computer-generated integral imaging and phase-modulation of hogel for red, green, and blue (RGB) channels of computer-generated hologram (CGH) using the generated 3D object via qualified single-image depth estimation-based approach. Finally, in the holographic printing part, the generated hogels are recorded into holographic material sequentially where SLM displays the R, G, and B channels of a single hogel via effectual time-controlled exposure under synchronized control with three electrical shutters for RGB laser illumination to provide full-color 3D reconstruction. Numerical simulation and optical reconstructions are implemented successfully, and the reconstructed 3D visualizations confirm that the proposed holographic printing system offers effective content generation for high-quality 3D visualization.

Keywords: Computer-generated hologram (CGH), holographic printer, holographic stereogram, computer-generated integral imaging, depth estimation

1. INTRODUCTION

Holography is a most promising 3D imaging technique, has been developed rapidly, and is used in many applications including 3D imaging displays, holographic optical elements (HOEs), and holographic printing [1, 2]. In recent years, holographic printing has been utilized to reproduce the optical function and realistic visualization of 3D scene within arbitrary sizes and desired specifications. It can be categorized into a few types such as HS printing, holographic fringe printing, and wavefront printing. Also, there are several researchers have proposed valuable research for HS printing [3-10]. In addition, a digital holographic printing that records a color image hologram with a full parallax of 120° is presented [11]. Also, an HS printing system with simple and fast computation for digital content generation using the inverse-directed propagation (IDP) algorithm is proposed [12]. Moreover, depth estimation is one of the effective methods that is utilized in several applications such as 3D imaging and scanning, background removal and separation, and 3D object rendering. Recently, depth estimation methods are proposed using effectiveness of modern convolutional neural networks (CNNs) [13, 14].

In this paper, qualified single-image depth estimation-based content generation for full-color holographic printing system is proposed. For the digital content generation, the depth estimation method is used to generate corresponding depth data from a single-shot image, and a 3D model is generated by combining the estimated high-quality depth data and 2D image, after that the array of sub-holograms (hogels) is generated within computer-generated integral imaging (CGII) and phase-modulation of hogel for holographic printing process. In the holographic printing part, the generated hogels are recorded into holographic material sequentially via full-color holographic printing system. Finally, the entire HS is obtained, and 3D visualization is observed successfully.

2. PROPOSED METHOD

2.1 Digital content generation

The schematic configuration of the proposed HS printing system is shown in Fig. 1. There are two main parts related to digital content generation; 1) acquisition of the 3D point cloud object of the 3D scene is implemented. Here, the depth estimation method is used to generate qualified depth data from a single-shot image, and a 3D model is generated by combining the estimated high-quality depth data and 2D image, then 2) the array of sub-holograms (hogels) is generated within computer-generated integral imaging and phase-modulation of hogel for red, green, and blue (RGB) channels of computer-generated hologram (CGH) using the generated 3D object via qualified single-image depth estimation-based approach. Finally, the HS is recorded on holographic material by providing full-parallax, full-color, and depth information.

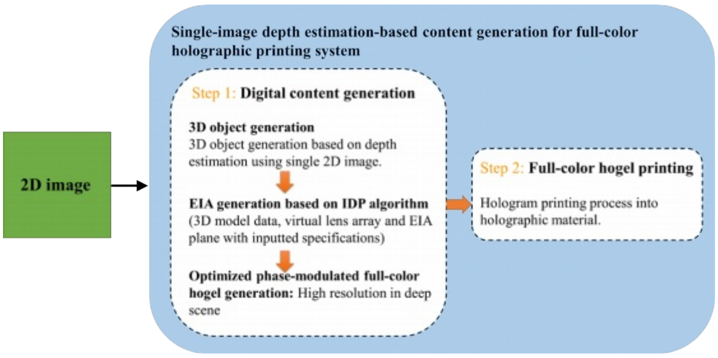

Figure 1. Schematic diagram of the proposed full-color HS printing system using depth estimation-based content generation.

In the digital content generation, the given 2D high-resolution image is modified and sent to the digital content generation. Then 3D object is generated according to the depth information that estimated using CNN based algorithm and 2D high-resolution image. After that, for the digital content generation of full-color hogel, the elemental image array (EIA) pickup is applied by using the simple and fast IDP [12] based on computer-generated integral imaging (CGII) from the generated 3D object.

3. EXPERIMENTAL RESULT

In the optical experiment, R, G, and B laser beam illuminations of HS printing system is implemented under the fully automated controlling GUI. The printed HS in Fig. 2 is composed of 58 × 75 hogels, the hogel size is 1mm x 1mm and the whole printing time for each printed HS is approximately 4.83 hours. For the optical experiment of full-color hogel printing, 3D visualization is observed clearly within full-parallax and depth information.

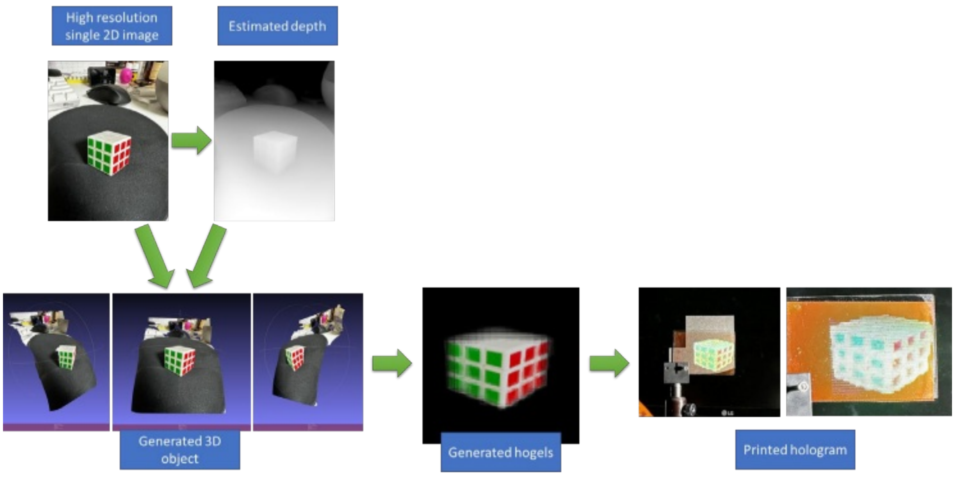

Figure 2. Entire process of digital content generation, and optical experiment result.

ACKNOWLEDGEMENT

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High-quality 3D model generation from real-world object based on the depth-position mapping for holographic display

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ABSTRACT

A holographic display for the three-dimensional (3D) model of the real-world objects is proposed. The depth-position map with advanced layering for deep neural network-based 3D model generation from real-world objects. A simplified light field image acquisition is taking the high-quality perspective images from a real-world object and generated high quality 3D model used deep neural network. By generated a high-quality 3D model, a high-quality depth map image and position map image were rendered. But the depth map image is capable of very good layering of near field objects, and far field objects cannot be layering with realistic depth values. However, the position map image is good layering of far field objects and ability to do layering is worse. We obtained the proposed advanced layering depth-position map method by combining these depth and position map images. By combining the depth and position maps, the real depth information of 3D model can be encoded accurately from near and far distances; accordingly, the layering process of 3D model is improved much. Our implemented deep neural network method quickly creates high quality 3D models based on ray tracing and volumetric rendering methods better than the depth camera and the 3D model generated in 360 degrees. Finally, the results were confirmed by numerical experiment and optical experiment by experimenting with layering of far and near field objects.

Keywords: Computer holography; Holographic display; Three-dimensional image processing; Neural networks.

1. INTRODUCTION

Holographic display (HD) technology has been developing more rapidly in recent years, and it has been trained by deep learning models to work better, faster and more reliably in real time [1]. In other words, as the methods of creating computer-generated-holograms (CGH) are more advanced and reliable, the reconstruction image is able to display more depth and parallax information. It is believed that the depth map value obtained using deep neural network is a more effective method for creating accurate reconstruction of the depth information of real-world objects. Because the method of using depth-camera to obtain the depth information of real objects is lossy. A real-depth camera is often used when an object containing three dimensional (3D) information of the real environment is used in a holographic display. It has a loss of resolution and depth accuracy is low, and it is not possible to create a reconstruction by layering a far field object with depth information. Because the depth map of a far field object is too bright, which makes layering difficult. Also, it is difficult to obtain real world objects without 3D loss in the computer [2]. The quality of holographic display reconstruction depends on the quality of the 3D model [3]. In most cases, the use of artificial data was related to the use of qualitative and 360-degree 3D models. However, in some cases, real-world objects are used for holographic display, but a depth camera is used for acquiring a 3D model. This is due to not being able to get a good enough quality 3D real-world model and also not being able to create a full 360-degree 3D model. However, the state-of-the-art instant-ngp method based on deep neural network has made it possible to create high-quality 360-degree realistic 3D models from perspective images of 3D real-world objects [4]. Depth map shows object depth information with 8-bit color accuracy, and it is important for 3D object layer division for holographic display. However, most real-world objects are layered using depth mapping when reconstructing for holographic displays, and it is difficult to obtain high-quality depth values [5]. The depth map has good accuracy for layering division of nearby objects, and it has difficulty in layering on distant objects. Therefore, position map was used to increase the accuracy of distant layering of this depth map. One of the features of the position map is the map image obtained by color encoding the 3D model, which does not change color regardless of the distance. However, layering a 3D model using a position map results in area loss due to color density.

2. RESEARCH PROGRESS

The principle scheme of the proposed integrated depth-position map consisting of 3 main steps is presented. High resolution data is needed to acquire high quality 3D model training, solved this data with our simplified acquiring system [2]. The simplified acquired data is acquired 360 degrees with a constant number of high-quality steps and works very well with the instant-ngp training model.

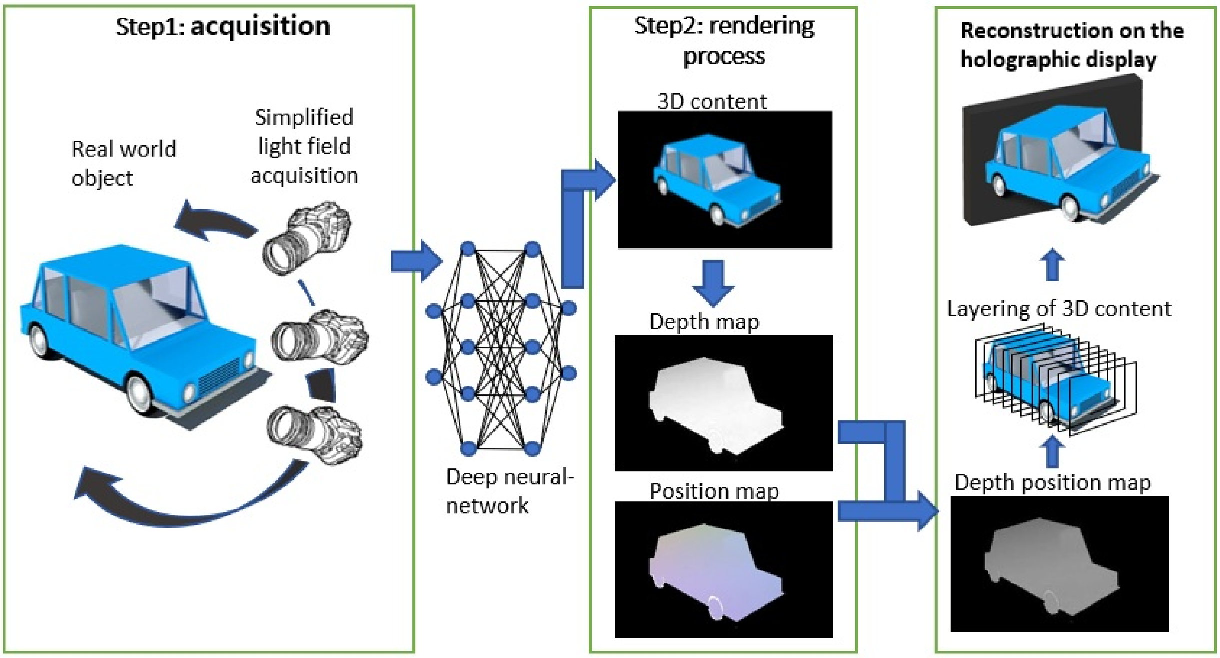

Figure 1. Schematic diagram of the proposed integrated depth-position map based on deep neural network for holographic 3D display

Instant ngp neural network method to create 3D model based on ray tracing and volumetric rendering approach, MLPs trained by multiresolution hash encoding method, optimizer and training process is accelerated. The 3D model, which was trained in high quality in a short period of time, can now render high resolution with 4k depth map and position map. However, the normal depth map was able to layer the 3D model at too near distance. However, for position map, it was better for layering objects located at a distance than at a close distance, and it was confirmed during the simulation. Therefore, it is advantageous to convert the rendered position map into grayscale 8bit color and make layering partition. Position map converting to grayscale, we using gamma compression correction ($C\gamma$) function and its gamma-expanded equivalent, which is the weighed sum of the digamma-expansion ($_F$) Red, Green, Blue (rgb) components.

$C\gamma$=([r,g,b]) => 0.2126_{F} (r) + 0.7152_{F} (g) + 0.0722_{F} (b)

NGP renders each pixel of a camera as follows: A ray r(t) = o + td is emitted from the camera's center of projection o along the direction d such that it passes through the pixel.

3. EXPERIMENTAL RESULTS

From the captured perspectives, the 3D model of the object is regenerated through a deep neural network which has a similar quality to the perspectives. Then, the advanced layering method process of the hybrid-mapping method renders the depth- and position-maps respectively from the generated 3D model. Note that the depth-map is more effective for near-field objects, and the position-map layers more effectively for far-field objects; and many losses occur. Also, these losses affect the final quality of the holographic display. Therefore, in order to keep the advantages and solve the issues of both methods and support the high-quality data to the system, the hybrid-mapping method is designed to provide an original view of entire far- and near-field objects. The accuracy of the layering of the entire 3D model can be improved much, compared to the independent depth- and position-maps.

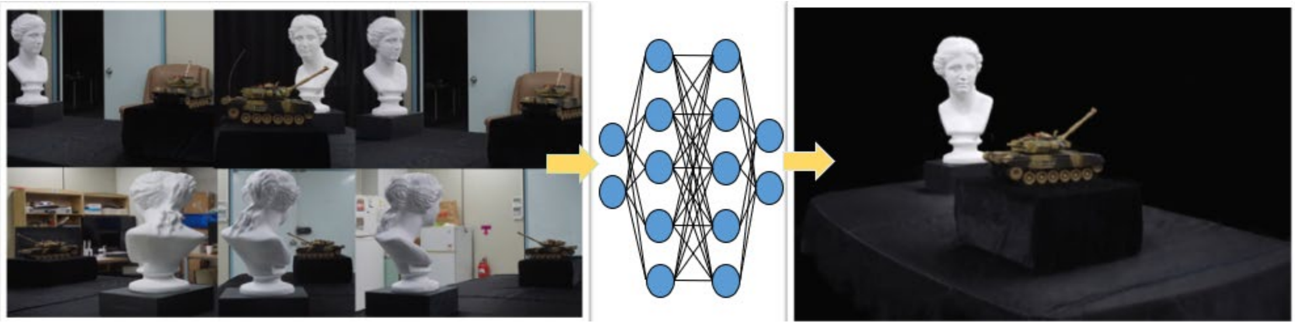

Figure 2. Perspective-view images of real-world objects and implementing instant neural graphics primitives generated 3D model

In the experiment, a simplified light field image acquisition system consists of three Sony α6000 cameras with a resolution of 6000×4000 pixels, the deep neural network training time is 80.3s and totally loss is 0.0058 with 97800 steps for generating 3D model from the real object, and rendering depth and position map image resolution has 1920x1080 increase to 4k, and optical reconstruction result provides natural-views with high quality for holographic displays. Acquired data consists of 48 images with tank and venus perspective images and

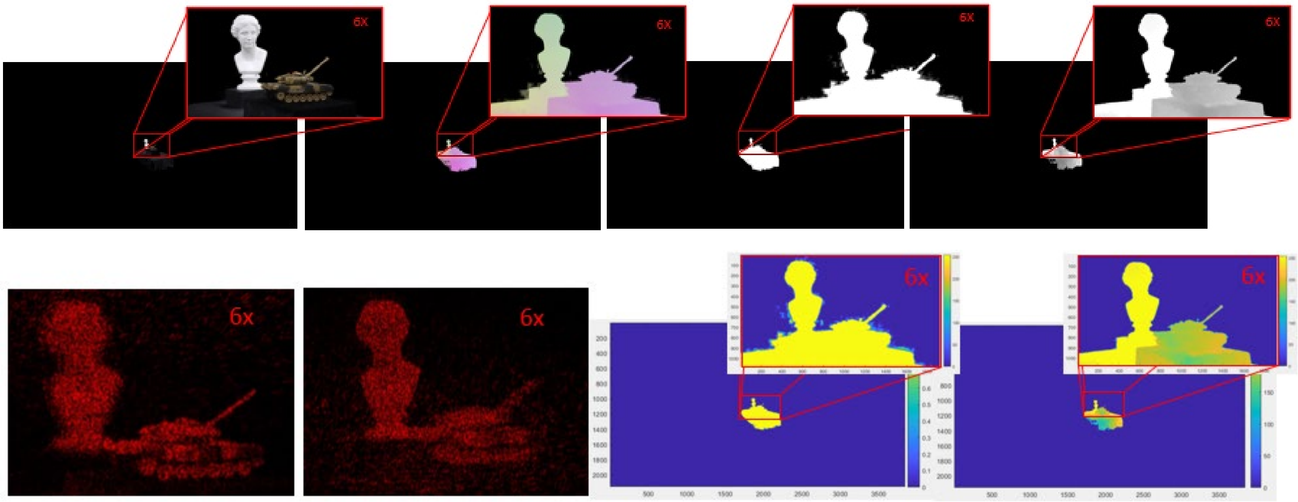

Figure 3. Far field object with 700cm distance from camera, zoom in 6x focused on tank and venus objects optical reconstruction and tested color map measuring of far field depth map and proposed IDP maps.

Rendered RGB, position map and depth map has 4k resolution with zoom in 6x and generate the angular spectrum depth based approach CGH displaying the SLM with red laser illuminations. Therefore, normal depth map and proposed integrated-depth mapping images compare the colormap measuring detection by red colors.

4. CONCLUSION

To display a fine-quality 3D representation of real-world objects on a holographic display, all inputs must be high-resolution and high-quality. In this paper, all stages of the proposed system provide high-quality and high-resolution data for CGH generation, and it gives an opportunity to obtain fine-quality 3D holographic images for real-world objects. In particular, the CGH generation stage should encode high-quality data. The proposed system utilizes two different deep neural network models, an instant-NGP model for 3D model regeneration, and an autoencoder-based model with U-Net architecture for CGH generation. The experimental results confirmed that the proposed system can be an effective method to implement the advanced holographic display system.

ACKNOWLEDGEMENT

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CHIMERA™ 180°, a Denisyuk printer

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ABSTRACT

CHIMERA™ technology has reached a new level with the CHIMERA™ 180°, the fourth generation of digital holographic printing system. Combined with a scanner designed in-house, the CHIMERA™ 180° printer is able to generate ultra-realistic full-color digital holograms with a 180° full-parallax, being a Denisyuk-like printer.

Keywords: Digital hologram, CHIMERA, Denisyuk, full-color hologram.

1. INTRODUCTION

In 1963 a famous kind of hologram was introduced by the Russian scientist Yuri Denisyuk and still used for museum, artistic, or educational applications[1,2], is the single-beam reflection technique[3] or 'Denisyuk hologram'. With this technique, it is possible to record at the same scale, full-color, full-parallax 180◦—horizontally and vertically—reflection analog holograms of real still objects. During the last 20 years, the development of diode-pumped solid-state (DPSS) lasers and color ultra-fine grain silver-halide recording holographic materials made that this technique of Denisyuk hologram became Ultra-realistic[4] and an observer hardly discriminates between the real model and its holographic counterpart[5,6].
In 1995 Yamaguchi et al.[7] proposed to record digital holographic stereogram divided into a matrix of small holographic elements or hogels. In 2019, the third generation of holoprinter called CHIMERA[8] by Gentet et al. is based on three low power red, green, and blue DPSS lasers combined with the silver-halide material ultimate U04[9], and prints digital holograms with a 50 Hz speed, a 120◦ full-parallax and a hogel resolution of 250 μm. CHIMERA holograms became ultra-realistic and offered a better accuracy in color rendering[10] than Denisyuk holograms. CHIMERA can be printed at any scale, mixed CG and real images, have multi-channel, and generate direct H2 pop-out images when Denisyuk holograms have scaling limitations—only real still objects and at a 1:1 scale. The last main gap between digital and analog holograms was the field of view, because Denisyuk holograms kept a larger full-parallax, 180◦ against 120◦ for CHIMERA. The last generation of CHIMERA printer, the 'CHIMERA™ 180°', combines now a scanner designed in-house and an opto-mecanical system so it is able to generate 180° holograms, reaching the stage to become the first Denisyuk-like printer.

2. MATERIALS AND METHODS

1.1 Material to record CHIMERA and Denisyuk holograms

CHIMERA and Denisyuk holograms were recorded on a silver halide holographic Ultimate U04 glass plate. This material was specially designed for recording full-color holograms without any diffusion and was set to be isopanchromatic for all visible wavelengths. The plates were developed in two safe and easy-to-use chemical baths.

1.2 CHIMERA™ 180° printer overview

The CHIMERA™ 180° uses three low-power RGB CW DPSS lasers with mechanical shutters that allow adjustable exposures in the range of 1 to 2 ms for each laser. The wavelengths are 640, 532, and 457 nm. To avoid any movement during the recording, an original anti-vibrating mechanical system has been specially developed. Each 250 μm hogel are recorded using three spatial light modulators (SLM) and a new 180◦ custom-designed full-color optical printing head. After being interfered with the 45 deg—or zero deg—reference beam the information corresponding to each RGB hogel is recorded into the U04 holographic material up to 60×80 cm with a print rate of up to 100 Hz.

1.3 In-house-designed scanner

An in-house scanner was designed to record full-parallax CHIMERA holograms of still object scenes as shown in Fig. 1. This scanner can automatically record a still object scene from 10×13 cm to 60×80 cm with a 4K camera and a controlled turning table. The scanner records a still object scene in 2 hours with 1200 horizontal images on a 180° rotation giving 180° of horizontal field of view and 192 elevation levels, giving +/- 40° of vertical field of view (80° in total). From the obtained perspective images, in-house software calculates all the hogels for the CHIMERA™ 180 printing.

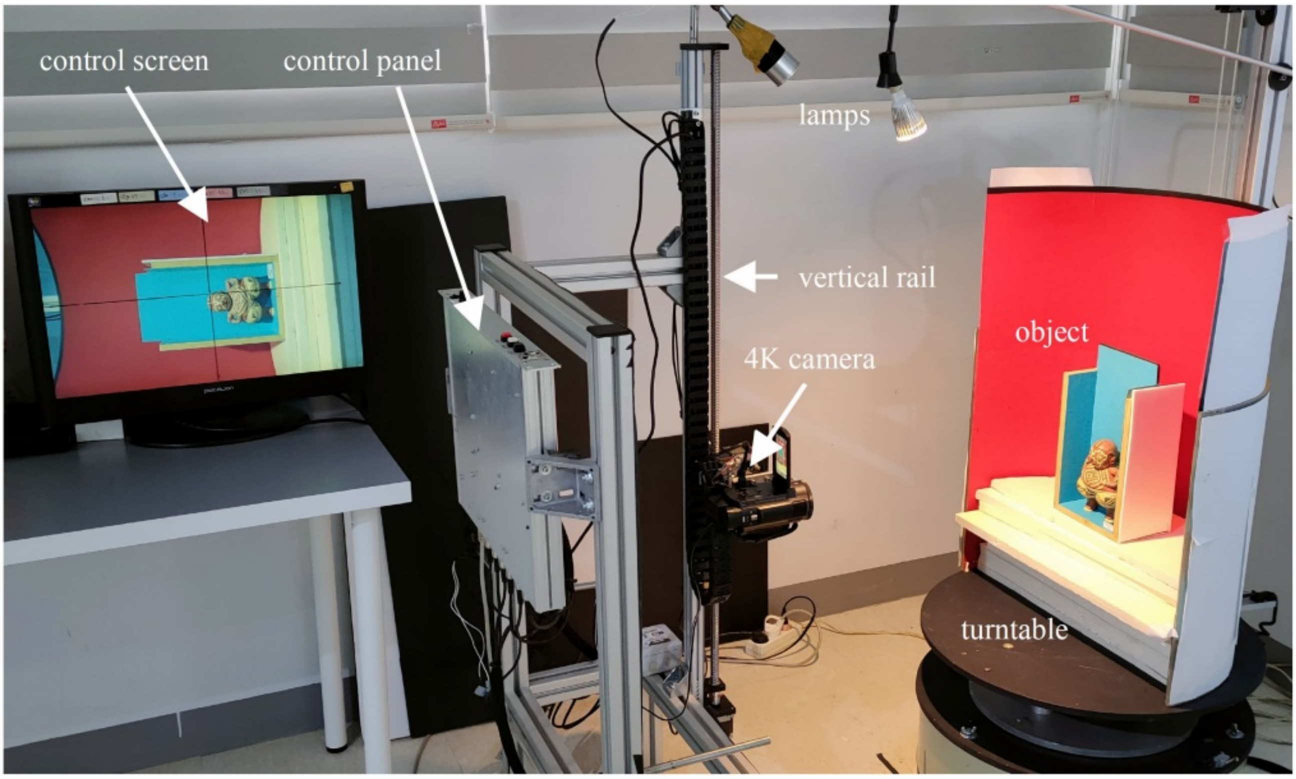

Figure 1. Acquisition of perspective images of a 3D scene with the in-house scanner. A 4K camera rotates on a 180° arc of a circle around the 3D scene, a real still object, to record a series of 768 horizontal images. The procedure is then repeated at 192 levels of elevation, thanks to the vertical rail, to create a cylinder of points of view.

1.4 Method to record Denisyuk holograms

A full-color Denisyuk setup used simultaneously a red, a green and a blue laser. The wavelengths were the same as for the CHIMERA™ 180°: 640, 532 and 457 nm. The three laser beams were combined and their intensities were adjusted to get a uniform white laser beam and were passed through the same beam expander and the same spatial filter. The divergent beam illuminates, with an angle of 45 deg, both the holographic plate and the real object. Denisyuk holograms were recorded with a mobile camera[11]—integrating the whole optical system in a box with dimensions 30×40×50 cm and mass 12 kg—specially designed to record images outside the holography laboratory and in particular directly in museums.

1.5 Sealing and illumination of holograms

To reconstruct the holograms to the same wavelengths used when recording, and to prevent any emulsion thickness variations due to changes in humidity or temperature, they were sealed with a second glass using optical ultraviolet (UV) glue. RGB light-emitting diodes (LED) currently offer the best solution of illumination because their wavelengths are centered on laser wavelengths[12].

3. RESULTS AND DISCUSSION

The same object, a green clown in a wooden box, was recorded using Denisyuk's method, then scanned and printed using the new CHIMERA™ 180° printer. The CHIMERA™ 180° hologram was printed on a scale of 1:1 and 250 µm resolution. Both 30×40cm holograms were then developed using two chemical baths and sealed with optical glue to prevent variations in the emulsion thickness. When the CHIMERA™ 180° (Fig. 2) and the Denisyuk (Fig. 3) were illuminated with an RGB LED lamp, a fine full-color and full-parallax reconstruction of the object was generated for both hologram.

Figure 2. 30×40 cm CHIMERA™ 180° hologram illuminated with an RGB LED. The hologram presents a complete 180 degree horizontal field angle.

Figure 3. 30×40 cm Denisyuk hologram illuminated with an RGB LED. The hologram presents a complete 180 degree horizontal field angle.

Both holograms presented a blur-free, ultra-realistic, colorful, transparent 1:1 scale image, with high DE for each wavelength and the same 180 degree horizontal field angle. The Denisyuk hologram keeps a better resolution but the 250 µm hogels of the CHIMERA™ 180° are invisible to the naked eye for a normal observer. The two holograms are virtually indistinguishable from each other, and only close, careful examination can detect a difference. The CHIMERA™ 180 printer is therefore capable of printing Denisyuk-like holograms.

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An attention mechanism-based CNN using RGB-Depth images for computer-generated holography

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ABSTRACT

In this paper, a method for generating computer-generated holography (CGH) using RGB-Depth images and an attention mechanism-based convolutional neural network (CNN) was proposed. Instead of using the conventional skip connection model, the attention mechanism was applied to emphasize high-frequency components. This structure enables the combination of RGB-Depth images and the attention mechanism to efficiently generated holograms while providing excellent reconstruction quality. The proposed method can effectively process the computation of complex objects and scenes.

Keywords: Attention mechanism, CGH, RGB-Depth Image, CNN

1. INTRODUCTION

Computer Generated Holography (CGH) is one of the core technologies for creating content for Holographic Displays by calculating the interference phenomenon between the complex optical wave, which contains the amplitude and phase distribution of the Object beam, and the Reference beam. Traditional CGH experiences computational difficulties due to the number and complexity of objects in a scene, resulting in limitations in quality improvement and scalability. To address these issues, various studies have been conducted to reduce the computation time of CGH. Recently, with the advancements of Convolution Neural Network (CNN)-based Deep Learning Methods, research showing high performance in various Computer Vision tasks has been conducted. Based on this development, studies applying these methods to CGH are being carried out. In this paper, a CNN-based CGH using the Attention Mechanism has been proposed for generating high-quality holograms.

2. RELATED WORK

2.1 Computer Generated Holography (CGH)

Light is a type of wave that possesses both intensity and phase. However, digital images record and reproduce only the intensity of light. In contrast, holograms record and represent both the intensity and phase of light, making it possible to record and reproduce a complete image in three-dimensional space. Therefore, holograms allow for freely observing depth and parallax changes within a given 3D space. Digital holograms can be directly recorded through an interferometer or indirectly calculated using Computer Generated Hologram (CGH) technology.[1] When directly acquired, lasers are used as the light source, as the interference phenomenon for hologram recording is easily achieved when the light source has coherent characteristics, like a laser. CGH can be calculated from various types of 3D image data, such as point clouds[2], meshes[3], color + depth images[4], and light fields[5].

2.2 Attention Mechanism

Attention was initially used in seq2seq to differentially apply features from previous inputs.[6] This attention mechanism is effective in learning to cope with the loss that occurs during the compression of a fixed-size vector in the encoder-decoder structure of seq2seq and the gradient vanishing problem that occurs when the input lengthens.[7] Recently, attention has been applied not only in seq2seq but also in CNNs as Self-Attention. In computer vision fields, such as object detection and semantic segmentation, the objects to be detected or segmented are not distributed throughout the entire image but rather in specific regions.[8-11] By emphasizing these regions and ignoring unnecessary areas, features are extracted. These features mainly extract location and semantic information and utilize the object's meaning and location features to improve network performance and show good performance even in inputs with significant noise.[12]

3. PROPOSED METHOD

In this paper, we proposed a CNN structure based on the Attention Mechanism. This structure takes a four-channel RGB-D image as input, and predicts a total of six channels of color holograms composed of RGB amplitude and RGB phase. Figure 1 shows the flowchart of the proposed method.

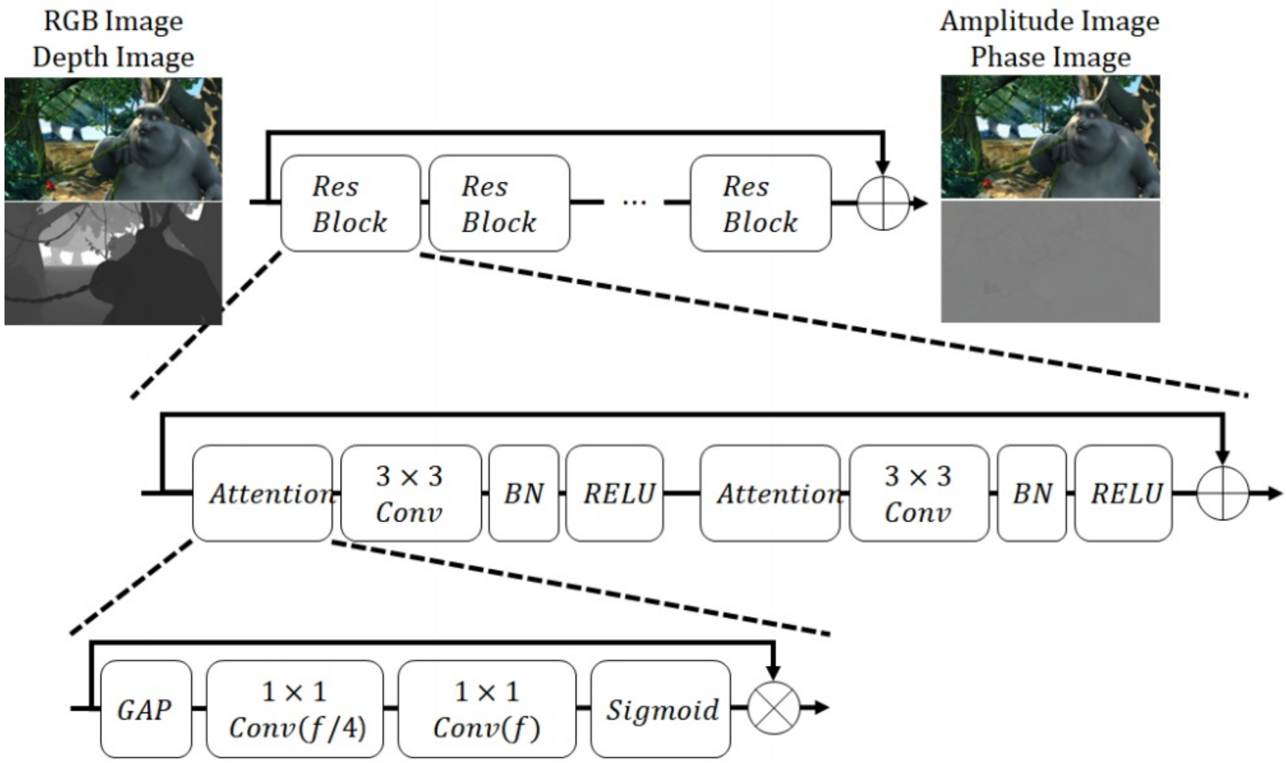

Figure 1. Proposed Method Flowchart.

The proposed method used data created by connecting RGB and depth images on a channel basis as input. Subsequently, the attention mechanism was employed to emphasize high-frequency features, and a ResBlock consisting of a 3x3 convolution, batch normalization, and a ReLU activation function is applied. By repeating the same process twice, and adding input feature maps using skip-connections, effective learning is enabled. In this case, the attention mechanism employs a channel attention structure, which is scaled down to a 1x1 size using global average pooling, and an attention map is generated with 1x1 convolution.

In the proposed network, the learning was conducted using L2 loss on the output Amplitude image and Phase image.

$$L_2(y, f(x)) = |y - f(x)|^2 \quad (1)$$

Equation 1 represents L2 loss, where y is the ground truth image, x is the input image, and $f(*)$ is the proposed network.

4. EXPERIMENTS AND RESULTS

The proposed network generated phase and amplitude images using RGB-depth images. The results of PSNR and SSIM are for the test set of the MIT-CGH-4k dataset. PSNR calculates the differences in signals using a log function, and the higher the value, the more accurate it is; when the generated image is identical to the original image, it outputs an infinite value. SSIM calculates structural similarity using luminance, and when the image is identical to the original, it outputs a value of 1. Table 1 presents the values of PSNR and SSIM for the proposed method. Figure 2 is an amplitude and phase image generated by the proposed method.

Table 1. PSNR and SSIM results of the proposed method

	PSNR	**SSIM**
TensorHolo mini [1]	-	0.92
TensorHolo small [1]	-	0.955
TensorHolo [1]	35.3	0.97
Proposed Method	40.420	0.996

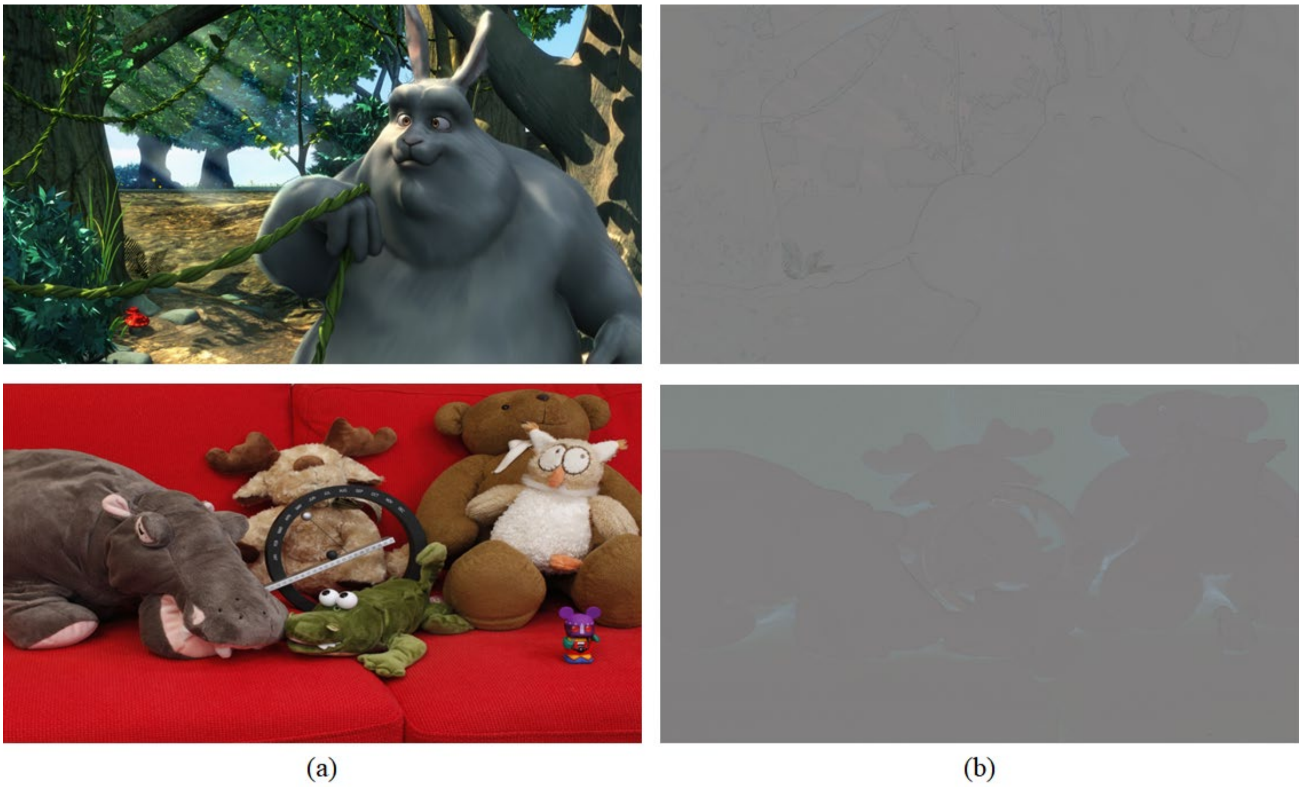

Figure 2. Result of Proposed Method: (a) Amplitude Image, (b) Phase Image

5. DISCUSSION

In this paper, we proposed a CGH using RGB-Depth images and Attention Mechanism. Processing high-frequency areas, such as object contours and textures, is crucial for generating high-quality holograms. To emphasize these features, we employed Channel Attention based on Attention Mechanism. The proposed method successfully generated high-quality Amplitude images and Phase images. Various CGH techniques need to be applied for high-quality holograms. In the future, it may be necessary to expand to different types of pipelines for hologram processing, and optimized CGH for real-time processing could potentially enhance the accessibility of holograms.

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Removing holographic noise of multiple particles by using shallow U-net model based on digital holography

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ABSTRACT

We propose a shallow U-net model with average pooling based on digital holography to restore multiple transparent particles at their ground truth z-positions in the water, while simultaneously remove their zero-order images, conjugate images, defocused images of other particles, and the noise associated with the optical system. Then, we obtain the lateral location and diameter of each particle centroid efficiently, eventually, acquire the particle density within the captured volume. A large training dataset is not essential for the proposed method (experimental training dataset of 100 images). The simulations and experimental results demonstrate that average pooling is more suitable than max pooling for training piece-wise patterns. In addition, average pooling can rapidly restore the in-focus images of particles with diameter ranging from 90-110 μm at the ground truth z-positions corresponding to a depth spacing equaling 100 μm, which is difficult to be achieved using conventional Fresnel diffraction (propagation). Finally, an approximation of the correct particle density is acquired. It also offers a quick and useful tool that can be applied to particle tracking tasks.

Keywords: Digital holography, U-net model, Fresnel diffraction, particles

1. INTRODUCTION

Digital holography (DH) can capture a volume, and reconstruct each plane of this volume, which is different from conventional microscopy that merely focuses a single plane. Sizing, counting, and locating issues related to in situ micro-objects (bubbles, particles, or microorganisms) have gained more and more attentions from particle image velocimetry (PIV) [1-6], cell kinetics [7-8], air and water pollution, and fuel injection and combustion *etc.*, especially with the development of in-line DH and its potential to be an alternative to conventional microscopy [9-10]. [11-14] employed spherical wave as the reference wave to illuminate different particles suspending in water. Their experimental configuration is very compact, and it provides a magnification of the target object. However, since the Fresnel diffraction is utilized, it reduced the field of view (FOV); further, the accuracy of the number of the particles and the location along the z-axis were significantly affected by the chosen depth spacing.

Compressive holography exhibits a good performance when encountering noise and ghost images, by transforming the hologram reconstruction problem to a regularized nonlinear optimization. Brady *et al.* introduced compressive sensing algorithm in DH, and demonstrated that decompressive inference can infer multidimensional objects from a 2-D hologram [15]. Chen et al. used a plane wave to illuminate bubbles [16], and they suggested the compressive holographic method to locate the axial position of each bubble; however, this method cannot distinguish the bubbles that are completely or partially overlapped along the z-axis. Total variation (TV) regularizer was employed in all the aforementioned papers. Tian *et al.* [17] suggested a 2-D hybrid-Weickert nonlinear diffusion (2D HWNLD) scheme in their research of transport of intensity equation (TIE) to efficiently remove the low frequency artifacts in an image. Li *et al.* [18] applied the 3-D hybrid-Weickert nonlinear diffusion (3D HWNLD) regularizer in DH, which can distinguish the locations of certain small-sized transparent scattering particles that are overlapped over the z-axis, to achieve a similar autofocusing of multiple micro-objects and simultaneously remove the defocused images. However, it cannot tolerate dense particles.

Ronneberger *et al.* [19] first propose the U-net model to deal with the issue of biomedical image segmentation using a small data set, it is fast as well. Li *et al.* [20] proposed a convolutional neural network (CNN) to learn the statistical information from a fully noise-like speckle intensity pattern, and successful recover the original image pattern. It is in fact a U-net model revised based on Ref. [19]. Goy *et al.* [21] proposed a deep neural network to restore objects illuminated with a weak light, they also demonstrated the loss function negative Pearson correlation coefficient (NPCC) can achieve a better performance. Wu *et al.* [22] demonstrated that cross-modality deep learning using a generative adversarial network (GAN) can endow holographic images of a sample volume with bright-field microscopy contrast. It bridges the contrast gap between coherent and incoherent imaging. However, the objects of aforementioned papers are large single object, or single plane object.

This work composes two missions. First, we propose a shallow U-net model with average pooling to remove their zero-order images, conjugate images, the defocused images of the particles, and the noise induced by the optical system, while simultaneously restore in-focus images of the other transparent particles at their ground truth z positions. Subsequently, we obtain the lateral location and diameter of each particle in a fast way; eventually acquire the particle density in the captured volume.

It is organized as follows: problem analyses and shallow U-net model with average pooling are introduced in Section 2. In Section 3, the experimental results are illustrated; moreover, the analysis is presented as well. Finally, the conclusions and future planes are summarized in Section 4.

2. PRINCIPLES

2.1 Problem analyses

When multiple transparent particles suspending in milli-Q water in a fully transparent cuvette, a plane wave illuminates the particles, then a hologram including the scattering light are captured by a CMOS (complementary metal oxide semiconductor camera). Hence, the whole volume is recorded in the hologram. Suppose there are totally *m* transparent particles, each particle $pcle_i(\xi,\eta)$ with different diameters and different distances z_i away from CMOS suspending in the volume *V*. The Fresnel diffraction of each particle is shown in Eq. (1) [23]. The complex amplitude of all the particles are the sum shown in Eq. (2).

$$H_i(x,y,z_i) = FT^{-1}\left\{\begin{matrix}\exp(jkz_i)\times FT\left\{pcle_i(\xi,\eta)\right\} \\ \times\exp(-j\pi\lambda z_i(f_x{}^2+f_y{}^2))\end{matrix}\right\}, \tag{1}$$

$$H(x,y) = \sum_i^m H_i(x,y,z_{\mathrm{i}}), \tag{2}$$

$$\begin{aligned} I(x,y) &= \left|R(x,y)\right|^2 + \left|H(x,y)\right|^2 + R^*(x,y)H(x,y) + R(x,y)H^*(x,y) + n, \\ &= 1 + \left|H(x,y)\right|^2 + H(x,y) + H^*(x,y) + n \end{aligned} \tag{3}$$

$$\begin{aligned} I_{final}(x,y) &= \left|H(x,y)\right|^2 + H(x,y) + H^*(x,y) + n, \\ &= H(x,y) + nse \end{aligned} \tag{4}$$

where (ξ,η), (f_x,f_y), and (x,y) represent the lateral coordinates of the particle's position, spatial frequency domain, and hologram plane, respectively; *nse* denotes the noise induced by the optical system; $1+\left|H(x,y)\right|^2$ represents the zero-order image; $FT\{\cdot\}$ and $FT^{-1}\{\cdot\}$ denote Fourier transform and inverse Fourier transform, respectively [23]; $H^*(x,y)$ denotes the complex conjugate of $H(x,y)$. In this application, the reconstruction performance of $H(x,y)$ is rarely affected by $\left|H(x,y)\right|^2$ and $H^*(x,y)$. Since it is a plane wave to illuminate the whole volume, the reference beam is assumed to be $R(x,y)=1$ for similarity in Eq. (3). Therefore the pre-processed hologram is presented in

$I_{final}(x,y) = I(x,y) - 1$. Moreover the pre-processed hologram is rewritten in Eq. (4) in which *nse* presents in $nse = |H(x,y)|^2 + H^*(x,y) + n$.

Since there are multiple transparent particles (for example, polystyrene beads) suspending in the milli-Q water. One raw reconstructed image generated from a pre-processed hologram (subtracting the collimating hologram) at a certain distance is composed of 5 components: the real images of in-focus particles, their zero-order images, conjugate images, the defocused images of other particles, and the noise induced by the optical system (especially the laser). The transparent particles suspending in water are plenty and small-sized, which turns out that the zero-order images and virtual images at the ground truth position are not the most significant artifacts to degrade the in-focus particles. The defocused images of the particles reconstructed not at the ground truth position interferes the quality of the in-focus particles.

2.2 Shallow U-net model with average pooling

The schematics of the in-line digital holographic optical setup is shown in Figure 1(a). In terms of that the transparent particles in the captured volume are plenty, small-sized, and independent from each other, deep U-net model would lose the features of small particles, which leads to certain small-sized particles missing. According to the particles are all homogeneous beads, each particle pattern at the ground truth *z* position is a piece-wise pattern, such as Figure 1(f), hence, average pooling can properly remain the particle size. Therefore, we propose a shallow U-net model with average pooling to remove the holographic noises while simultaneously restore the in-focus images. The structure of the proposed shallow U-net model is shown in Figure 1(d), which consists of two down-samplings and two up-samplings.

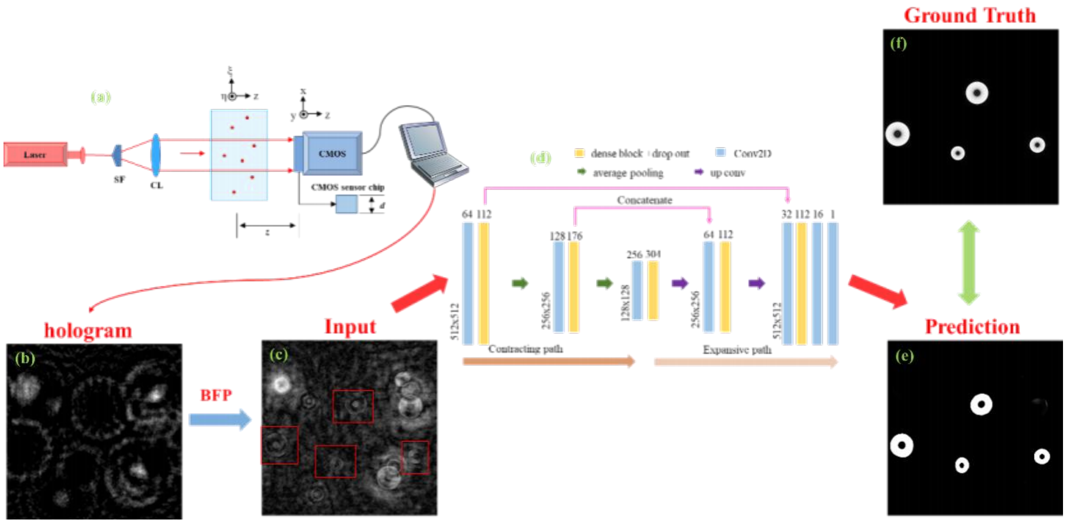

Figure 1. (a) Schematics of the in-line digital holographic optical setup (SF: spatial filter, CL: collimating lens, z: transmission distance between object plane and hologram plane, d: the height of CMOS sensor chip); (b) one pre-processed hologram including multiple particles; (c) one raw reconstructed image at a certain distance by using backward Fresnel propagation (BFP), which is also an input of (d) the shallow U-net structure with average pooling; (e) is the prediction image of the trained proposed model corresponding to (c); and (f) is the ground truth of (c).

The input image is the raw reconstructed image generated from pre-proposed hologram $I_{final}(x,y)$, such as Figure 1(b), One instance of the input image is shown in Figure 1(c) by utilizing backward Fresnel propagation of Figure 1(b), and the areas encompassed by the red solid line are in-focus image of the particles. Defocused images (of other particles) also include real images, virtual images, and zero-order images of other particles. We choose the raw reconstructed images as input images instead of holograms, otherwise, neural network would carry out the burden of learning the law of Fresnel diffraction [21]. Namely, neural network not only learns the principles of Fresnel diffraction, but also learns the denoise function. When compiling the proposed model, negative Pearson correlation coefficient (NPCC) is used as the loss function [21], which is described in Eq. (5).

$$NPCC(A,B) = \frac{-\sum_i (A_i - \overline{A})(B_i - \overline{B})}{\sqrt{\sum_i (A_i - \overline{A})^2 \sum_i (B_i - \overline{B})^2}} \tag{5}$$

where *A* denotes the input image, *B* denotes the prediction image after trained by the proposed shallow U-net model; A_i and B_i present each pixel value of *A* and *B*; $\overline{A}$ and $\overline{B}$ are the mean values of *A* and *B*, respectively.

3. RESULTS AND ANALYSIS

3.1 Experimental results

Figure 2(a) is the experimental setup, in which the wavelength of the laser is 632.8 nm, the size of the CMOS is 2046 by 2058, and its pixel pitch equals 3.45 µm. A hologram (1536×1536) is generated by capturing a volume with 500 polystyrene particles per ml milli-Q water (diameter = 90~110 µm). It is shown in Figure 2(b). In the experiment section, the raw reconstructed images in the dataset are generated by the reversed holograms $I_{revs}(x,y)$ where $I_{revs}(x,y) = 255 - I(x,y)$,similar to Figure 2(b), and the corresponding ground truth images were generated using the morphological method outlined in [12]. Note that the bad data was eliminated manually as the method in [12] is not stable and accurate. We assigned 100 raw reconstructed images (measuring 512×512 pixels) as the input images forming the training dataset, and trained the proposed short U-net model for 60 epochs, lasting 120 minutes in total. Subsequently, we acquired the short U-net model with trained parameters. As the proposed short U-net model is trained to find the in-focus particles in the raw reconstructed images, individual raw reconstructed images do not interfere with each other. In the test section, a stack of raw reconstructed images, shown in Figure 2(c), were generated at distances ranging from 67 to 82 mm away from the CMOS with a reconstruction depth spacing equaling 100 µm. Owing to the capacity of the GPU, we were restricted to training raw reconstructed images with sizes of 512×512 pixels, and we chopped each large raw reconstructed image into 9 small pieces with a size pixels in order to feed them conveniently into the trained shallow U-net neural network, shown in Figure 2(d). Subsequently, we merged them to form a large prediction image, as shown in Figure 2(e). Eventually, the corresponding stack of prediction images, shown in Figure 2(f), can be rendered as a 3D volume, as depicted in Figure 2(g). We also tested several other holograms which was captured at the time around when the hologram Figure 2(b) was captured, the detected particle numbers were all approximate with each other.

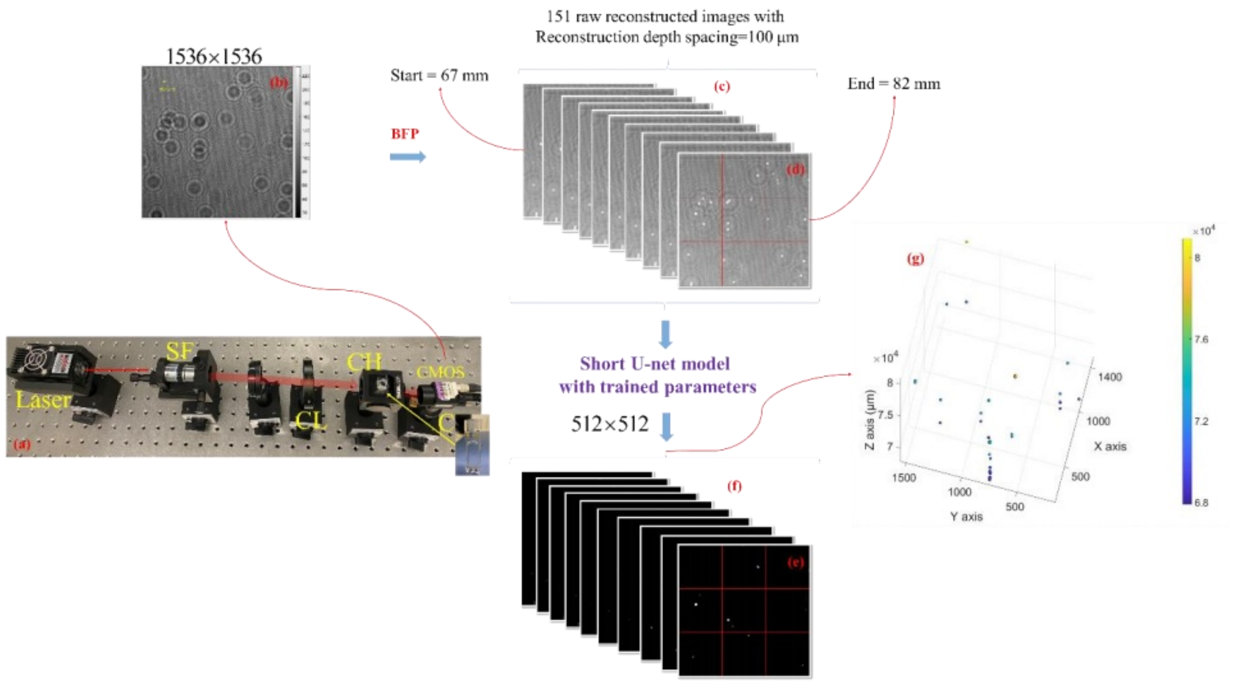

Figure 2. Experimental results: (a) experimental setup, SF: spatial filter, CL: collimating lens, CH: cuvette holder (CVH100/M, Thorlabs), C: cuvette ($12.5 \times 12.5 \times 45$ mm^3); (b) example of a captured hologram(1536×1536) acquired using the setup in (a); (c) a

stack of raw reconstructed images (1536×1536) in terms of (b) at distances ranging from 67 to 82 mm from the CMOS; (d) each raw reconstructed image is subdivided into 9 equal sections (512×512); (e) the combination of the 9 predicted images corresponding to the sections in (d); (f) the corresponding stack of prediction images in terms of (c); (g) particle distribution of the hologram in (b) translated to 3D space.

3.2 Evaluation and discussions

The particles can be efficiently restored according to Figure 1(e) and Figure 2(f), with each particle exhibiting a circular shape, Consequently, we can find these circles and locate the lateral position of each particle, including the center coordinates and, the diameter of each particle, as depicted in Figure 2(g). We detected 96 particles with a diameter larger than 90 μm within a captured volume of mm3. After counting the total number of particles in the whole captured volume, the density was determined to be 240 particles per mL. Interestingly, this calculated density is less than the density value we assumed initially. There are three potential explanations for this observation: first, the particles concentrate at the bottom of the cuvette, and therefore we captured only the sparse volume; second, some errors occurred when making the original particle solution; third, the conventional method of generating labels fed into the proposed model, which is described in [12], does not accurately account for the complexity that results from the combination of the particle size and the reconstruction depth spacing. However, the simulations and the experimental results produced using the proposed method is promising. In addition, the time taken to obtain the prediction of a hologram was less than 2 minutes, which is much faster than both the conventional method and compressive DH. Because the raw reconstructed images are trained to match the ground truth images using the proposed short U-net model with average pooling, we infer that it implies the trained parameters are highly reliant on the pre-produced ground truth images; this is illustrated by the quality of the simulation results.

4. CONCLUSIONS AND FUTURE PLANS

We proposed a shallow U-net model with average pooling to restore real images of in-focus multiple transparent particles at ground truth z-positions, while simultaneously removing their zero-order images, conjugate images, the defocused images from the other particles and the noise associated with the optical system. Subsequently, we obtained the lateral location and diameter of each particle efficiently, and eventually acquired the particle density within the captured volume. For our proposed short U-net model (experimental training dataset of 100 images), a large training dataset is not essential. The simulations and experimental results demonstrate that average pooling is more suitable than max pooling for training piece-wise patterns. In addition, average pooling can distinguish the in-focus images of particles with diameter ranging from 90-110 μm at the ground truth z-positions corresponding to a depth spacing equaling 100 μm, which is difficult to achieve using conventional Fresnel propagation in 2 minutes. Eventually, a close approximation of the correct particle density is acquired. The proposed method also offers a fast and useful tool that can be applied to particle tracking tasks.

However, since the proposed shallow U-net model with average pooling is a supervised neural network model, it acquires labels (ground truth images) when training the dataset. Hence, it is difficult to produce labels in the real world, which is also the main reason for that our experimental results are not accurate, therefore, the proposed neural network model should be expanded to unsupervised neural network without using labels.

5. FUNDING

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Neural network-based robust full-complex hologram watermarking

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ABSTRACT

In this paper, we propose a novel approach for deep neural network-based robust hologram watermarking using a robust feature extractor module. Our proposed method is designed to embed a hologram watermark into an original hologram in a robust manner that can withstand various attacks while maintaining high fidelity to the original image. To achieve this, in previous research, we considered PSNR during training. However, since holograms exist in the complex domain, it is necessary to consider the SNR of complex numbers to verify the reconstructed results. Moreover, we proposed an Enhanced Network with increased depth to improve performance by enhancing the robustness of the watermark against common image processing attacks. Experimental results show that our method outperforms existing methods in terms of robustness and fidelity under various types of attacks, including Gaussian filter, Salt & pepper Noise, and median filter etc. Our approach is expected to have wide-ranging applications in various fields, including digital image authentication, copyright protection, and data security.

Keywords: Digital hologram, digital watermark, deep neural network (DNN), convolution neural network (CNN), security

1. INTRODUCTION

Digital holograms are ultra-high-value content. To distribute this content, it is necessary to protect intellectual property rights from modulation, demodulation, and content forgery. Recently, digital watermarking has been mainly studied in that way [1]. Watermarking is the technology that inserts the owner's information(watermark) into digital content and extracts the information to claim ownership. In watermarking, two characteristics of invisibility and robustness are important. Invisibility is to hide that watermark is embedded so that it cannot be distinguished from the naked eye. Robustness is a characteristic that prevents watermark information from non-malicious attacks and malicious attacks that occur during the distribution and storage of content. This study also deals with watermarking the characteristics of invisibility and robustness. In digital hologram watermarking, algorithm-based methods have been studied so fa [2][3][4].

On the other hand, the recent technology trend of digital watermarking is using deep learning. Deep learning-based technologies perform well in the digital watermarking of 2D images [5][6][7]. However, it is in the early stages. Kang first proposed a digital hologram watermarking network with attack simulations inserted inside a deep neural network and a network with a resolution converting network, watermark embedding network, and watermark extracting network structure [8].

This paper proposes a deep neural network that performs digital hologram watermarking through deep learning with improved robustness using the robust feature extractor module. First, the proposed network extracts the watermark feature and robust hologram features against attack. Then, after concatenating the two features, it embeds a watermark through an additional layer. Finally, the watermark is extracted through an extraction network. Because the hologram consists of 2D data of the complex plane, the proposed network use SNR of the complex number as a loss function during training. Through experiments, it is verified that the proposed network shows improved performance of the previous work

2. PROPOSED METHOD

Figure 1 shows the proposed hologram watermarking network. The network comprised the watermark embedding network and the watermark extracting network. The data of the amplitude hologram was composed of [-1, 1]. In addition the watermark was composed of 1 or –1 in binary format.

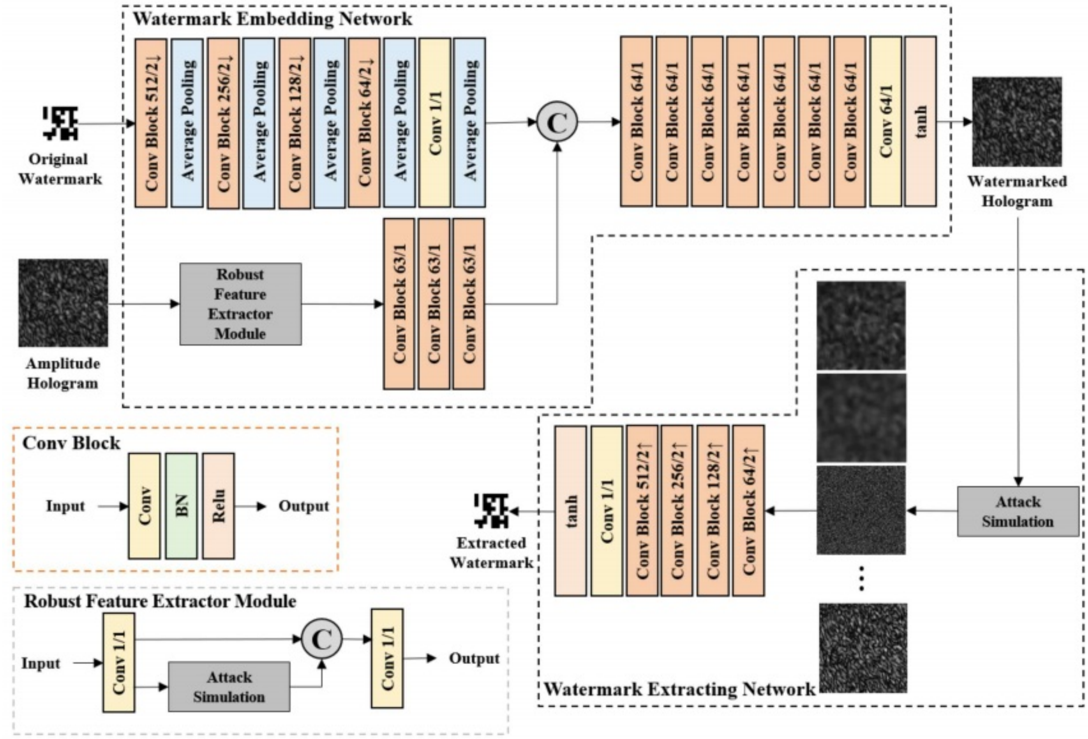

Figure 1. Structure of the proposed method

2.1 Detailed structure of the network

All networks use 3×3 convolution. First, the watermark is adjusted to the same resolution as the original hologram using conv block and pooling. Conv block comprised convolution-batch normalization-ReLU(activation). The last layer used convolution and pooling. All of the pooling is average pooling. The reason is that watermark data has a binary value unlike amplitude hologram, which uses real numbers. Therefore, it alleviates the difference between the two data by average pooling.

In addition, original holograms extract attack-resistant features through the robust feature extractor module. After going through three Conv Blocks, the watermark feature and concatenate are followed by a full-fledged watermark embedding process. Next, the watermark embedding process goes through seven Conv Blocks, and finally, the hologram with the watermark embedded hologram is extracted using convolution and tanh. Finally, Tanh is used as an activation function for the last block so that the output has a value in the range of [-1, 1] like host data.

Attacks on holograms are included in the training process for robustness, as can be seen in the network structure. When a watermark is embedded after performing an attack simulation on the original hologram, the training is performed in robustness form during the training process of embedding the watermark.

Various attacks are applied through attack simulation to a watermarked hologram, and an attacked and watermarked hologram is generated. Here, the watermark is extracted through the watermark extracting network. Attacks are Gaussian blurring, average filtering, median filtering, salt & pepper noise, Gaussian noise, and sharpening.

2.2 Loss function

The loss function between the original and extracted watermark is binary data, so the mean absolute error (MAE) is used. It is shown in Equation 1. The hologram contains 3D image information and consists of 2D data of a complex plane to express it. Therefore, in training, we consider SNR of complex numbers[9]. The formula for this is shown in Equation 2. Moreover, for holograms, reconstruction results are important. Therefore, we train with the MSE between the reconstruction results of the original hologram and the watermarked hologram. It is shown in Equation 3. Among the three loss functions, L1 and L2 are used to learn the watermark embedding network, and L3 is used to train the watermark extracting network. The resolution of holograms is M×N, and the watermark is X×Y.

$$L1=\frac{1}{XY}\sum_{i=0}^{X-1}\sum_{j=0}^{Y-1}|WM_{ori}(i,j)-WM_{ext}(i,j)| . \quad (1)$$

$$CD=\sqrt{(H_{Re,x}-H_{Im,x})^2+(H_{Re,y}-H_{Im,y})^2+(H_{Re,z}-H_{Im,z})^2}. \quad (2)$$

$$L2=10\log_{10}\left(\frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}|CD_{ori}(i,j)|^2}{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}|CD_{ori}(i,j)-CD_{wmk}(i,j)|^2}\right). \quad (3)$$

$$L3=\frac{1}{MN}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}|H_{ori}(i,j)-H_{ext}(i,j)|^2 . \quad (4)$$

3. EXPERIMENTAL RESULT

The proposed method was programmed using Python and TensorFlow. The experimental environment used two Intel(R Core(TM) i7-6700 CPUs @ 3.40 GHz with Nvidia RTX 2080. The batch size was 80, and the network was trained 1000 times. The initial learning rate is 0.0001, and the Adam optimizer was used as the optimizer.

To measure the watermarking performance, we evaluated the invisibility using SNR of the complex number and for PSNR between the original and watermarked hologram and the robustness using the BER(bit error ratio) between the original and the extracted watermarks.

The standard data set [10] provided by JPEG Pleno can be classified into three main types (ERC, B-com, and UBI) depending on the method and institution created. Forty-six types of hologram data are provided, and these holograms are divided into amplitude and phase and R, G, and B channels of color images. We randomly chose it and used it for training. The hologram size for training was 128×128, composed of 5,000 training data and 1,000 test data.

Table 1 shows the average BER, SNR of the complex number, and PSNR. In the case of invisibility results, we got good invisibility with an SNR of 33 and PSNR of 41.62. For robustness, the proposed method was improved by 0.42 than previous work.

Table 1. Result of reconstructed host data in PSNR & SNR(complex number) and extracted watermark in BER.

Attack	Previous work [29]	Proposed method
SNR(complex number)	32.82	33.19
PSNR	42.01	41.62
Gaussian Blurring(3×3)	1.69	1.51
Average Filtering(3×3)	5.45	5.21
Median Filtering(3×3)	2.15	1.98
Salt & pepper Noise(0.05)	5.54	2.67
Gaussian Noise(005)	4.23	3.57

Sharpening(3×3)	3.55	3.13
Average	3.76	3.01

4. CONCLUSION

In this paper, a method of performing watermarking on digital holograms using deep learning was proposed. The proposed method comprises a watermark embedding network and a watermark extracting network. In addition, the method proposed by the watermark embedding network improved robustness using the robust feature extractor module, and the SNR of the complex number was applied during training. As a result, the proposed method obtained a 0.42 improvement in robustness compared to previous work while keeping SNR similar. Therefore, our approach is expected to have wide-ranging applications in various fields, including digital image authentication, copyright protection, and data security.

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Quantization table extension for the holographic compression of JPEG Pleno

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ABSTRACT

This paper describes a quantization method for efficiently compressing the real and imaginary parts of full-complex holograms. In the context of JPEG Pleno, standardization efforts are underway for compressing full-complex holograms. Among various representation methods for holograms, full-complex holograms are commonly used. They provide a complete mathematical representation of the interference and diffraction phenomena of light propagating in space. However, compressing full-complex holograms is challenging due to their visually noisy appearance, resembling noise, and they pose difficulties in compression. Furthermore, preserving the relationship (phase) between the real and imaginary parts is as important as maintaining the image quality of each part individually. Thus, when compressing the real and imaginary parts of holograms separately, it is crucial to preserve their relationship.

The Interfere Codec used in the JPEG Pleno's hologram compression standardization project is a newly developed codec based on the hologram-specific compression method devised by ERC Interfere. During the encoding process, the codec performs a Short-Time Fourier Transform (STFT) operation and applies first-order quantization on the coefficients in units of Xmax. It then follows with a second-order quantization in units of Qmax. The data is quantized in units of Qmid, Qmax, and Qbitdepth, and this information is stored in one quantization table per tile and transmitted in the bit-stream, allowing the encoder and decoder to reference it.

This paper presents a new approach in the context of Rate-Distortion Optimization (RDO) to efficiently compress holograms while preserving the relationship between the real and imaginary parts of full-complex holograms. This is \achieved by employing multiple quantization tables during the RDO process.

Keywords: hologram, compression, quantization, reconstruction

1. INTRODUCTION

1.1 Holography

Holography, first proposed by Gabor in 1948 [1], continues to be extensively researched and developed in various fields due to its ability to fully record three-dimensional information. Analog holography, which records three-dimensional information on holographic film made of special materials and utilizes the developed film, has limitations for modern multimedia applications [2]. To overcome the drawbacks of analog methods and fully exploit the three-dimensional reconstruction of holograms, research on digital holography has been widely conducted [3]. Digital hologram signal processing is necessary to utilize digital holograms as a multimedia tool [4]. Hologram signal processing consists of hologram rendering and compression. Hologram rendering technology includes hologram generation, editing, display, interpolation, and enhancement. Hologram compression technology involves compression of still holograms and video holograms. Currently, JPEG Pleno is standardizing the compression process for still holograms [5]. In this regard, a comprehensive and concise discussion of various hologram compression methods proposed or attempted previously is presented.

1.2 Compression using standard codecs

Numerous research studies have analyzed the impact of quantization on holograms. In the past, uniform quantizers were primarily used, and scalar quantization considering hologram pixels was commonly employed [6]. Recently, research has extended to vector quantization, which performs quantization at the block level [7]. Additionally, scalar quantization has been investigated using both uniform and non-uniform quantizers. Analyzing the research results based on the normalized standard deviation (NSTD), it was observed that uniform quantization performed well when using low quantization bits (high compression), while the K-medians clustering approach showed better performance with high quantization bits (low compression). However, the difference between them was minimal. Overall, the K-means clustering approach exhibited low performance across all quantization bits. These research findings indicate that computationally intensive and complex vector quantizers do not necessarily yield superior performance in hologram quantization.

In recent years, various studies have focused on compressing holograms using standard codecs such as JPEG, JPEG2000, AVC, and HEVC, benchmarking their compression efficiency [8][9][10].

There are several common considerations when using standard codecs. First, it is necessary to convert the complex hologram in floating-point format into 8-bit integer data to input it into the standard codec. Second, adjusting the parameters of the codec is crucial. Each codec offers various adjustable parameters. For example, in the case of HEVC, when using the Intra mode, parameters such as QP (quantization parameter) and CU (coding unit) size can be selected. Differences in preferred parameter settings can lead to variations in the results.

Research on hologram compression can be divided into two main categories: compressing the hologram itself and compressing the information of the diffracted (reconstructed) plane at a specific distance after propagating the hologram [11][12][13][14]. Most of the methods discussed so far have been attempts to compress the hologram itself. Holograms have a noise-like nature, making it challenging to find spatial correlations among pixels, and even performing frequency transforms may not exhibit good energy concentration. Therefore, the compression approach in the reconstruction domain involves transforming the hologram into a form with higher spatial correlation and then compressing it. Our discussion focuses on research related to compressing the hologram itself.

2. RELATED WORK

2.1 Interfere Codec

The Interfere Codec is a newly developed codec that implements a hologram-specific compression method proposed by ERC interfere. ERC interfere is one of the research groups dedicated to exploring and developing new approaches for compressing hologram data. They are actively involved in the standardization efforts for hologram data compression within the JPEG Pleno project. The Interfere Codec is still undergoing standardization and further research and development are being conducted through the JPEG Pleno project.

2.2 Flow of process of the Interfere Codec

The existing encoding method of the Interfere Codec for hologram compression involves performing the Short Time Fourier Transform (STFT) operation on complex holograms. The coefficients obtained are then quantized in two stages: first, a first-order quantization is applied with a unit size of Xmax, followed by a second-order quantization with a unit size of Qmax. Through the first Rate-Distortion Optimization (RDO) process, suitable Xmax values for coefficient quantization are determined and organized in an RDO table. Subsequently, the second RDO process is performed to identify the appropriate Qmid, Qmax, and Qbitdepth values that yield the smallest distortion based on the target Signal-to-Noise Ratio (SNR). The quantization table, based on the RDO table, is then used to perform the second-stage quantization of the Xmax data. This information is included in one quantization table per tile, which is transmitted in the bit-stream for reference by the encoder and decoder. Prior to quantization of the complex hologram, tiling is necessary to divide the hologram into encoding regions. The current approach used in the Interfere Codec involves referencing one quantization table per tile for a single complex hologram.

Generally, tiles are set to be the same size as the entire hologram to avoid the prominent blocking effect that occurs when quantization is performed after increasing the number of tiles. Since the quantization tables are processed independently for each tile, higher compression ratios lead to significant errors at the boundaries of adjacent tile regions. Therefore, the default setting is to use one quantization table for one tile, which is set to have the same size as the hologram. As a result, only one quantization table is referenced for quantizing a single hologram.

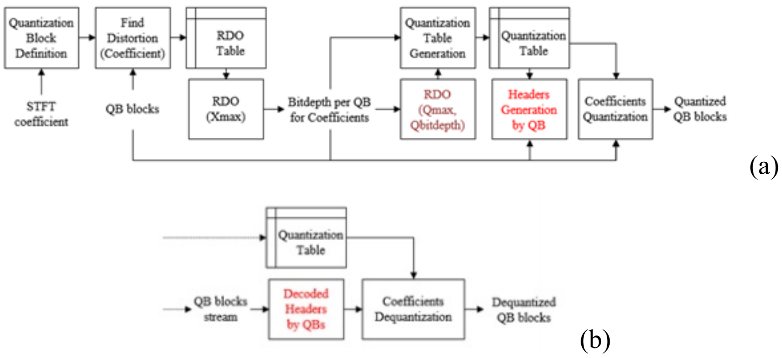


Figure 1. Interfere Codec Flow (a) Encoder, (b) Decoder.

3. PROPOSED CODING METHOD

3.1 Proposed Method

Figure 2 depicts the structure of the proposed codec, illustrating the encoding and decoding flow. The key idea of the proposed approach is to perform the 2nd RDO process, during which an Extension Table is generated by masking a certain range from Qmid. This Extension Table is then utilized, while the remaining portions that do not fall within the mask are handled using the existing table.

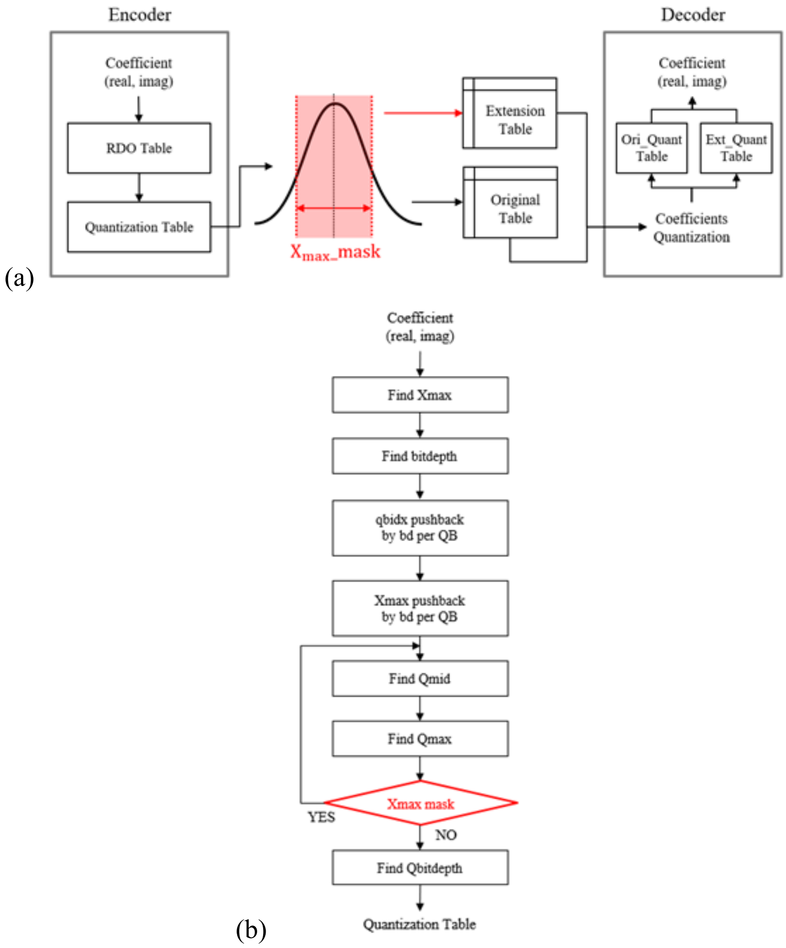


Figure 2. Structure of the main process of the proposed algorithm. (a), (b)

For the ratio, several experiments were conducted using arbitrary values of 1/2, 2/3, 3/4, 4/5, and 5/6. In the following description of the experiment, we will focus on the results obtained with the ratio of 4/5, which showed the best performance.

4. EXPERIMENTAL RESULT

In this chapter, we describe the compression results of the proposed Codec. Firstly, we introduce the experimental setup, followed by an analysis of the compression results and their corresponding visual outcomes. Finally, we present optical restoration results and comparisons with the JPEG2000 and HEVC Codecs.

Common Test Conditions (CTC) for JPEG Pleno Holography are typically used to evaluate the performance of Codecs. CTC refers to predefined standardized test conditions for evaluating JPEG Pleno Holography, including additional proposed research and experimental performance evaluations. These conditions allow for comparing various compression algorithms and codecs for holography data and provide criteria for improvement.

In the subsequent experiments, we evaluated the performance of the proposed Codec using Deepdice2K holograms, based on CTC v9.0 Table 10 as the benchmark.

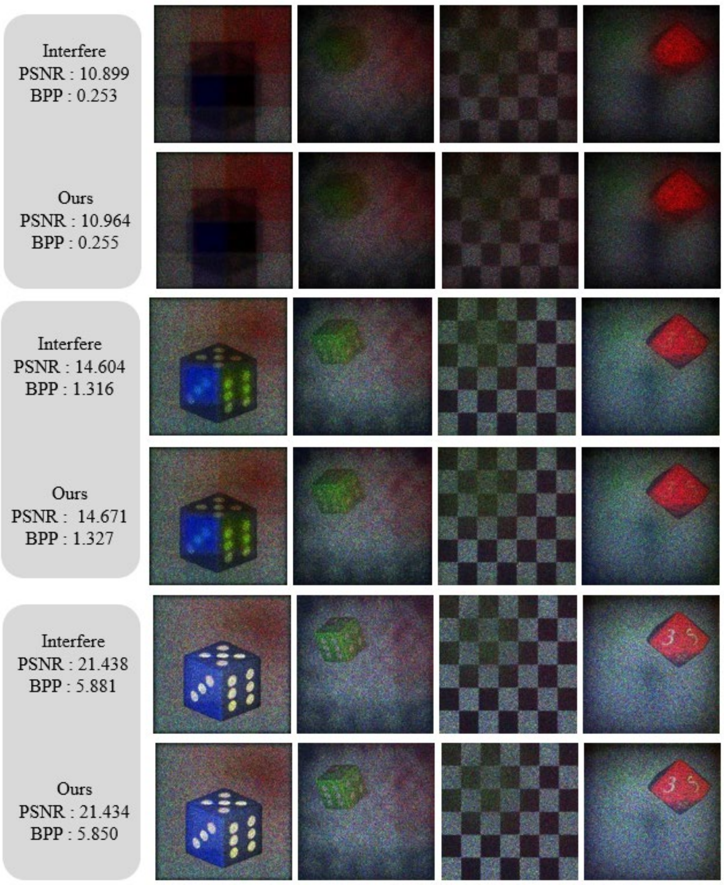
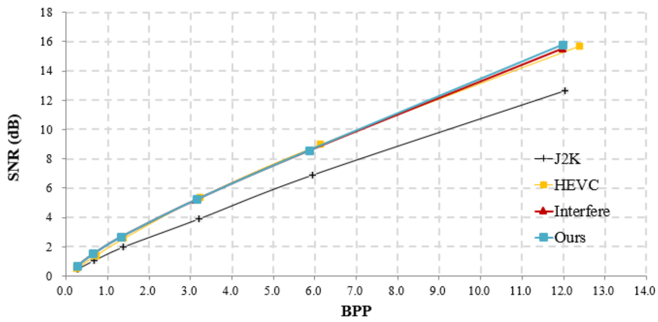
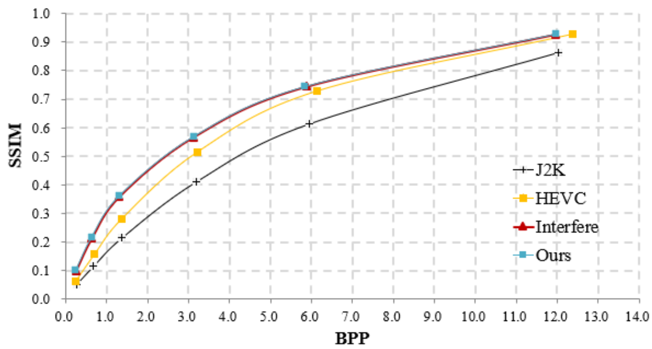


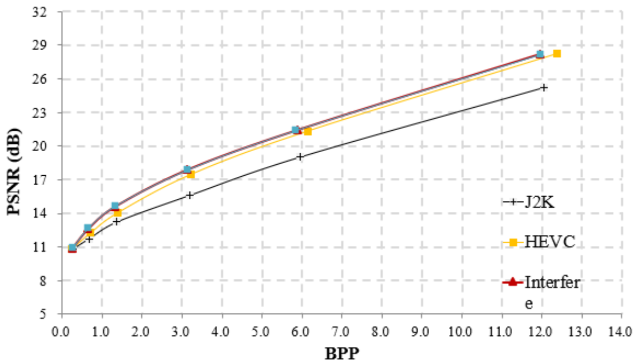
Figure 3. NRSH (Numerical Reconstruction Software for Holography) at Target SNR (a) 0.71, (b) 2.71, (c) 8.66



(a)



(b)



(c)

Figure 4. (a) SNR (b) SSIM (c) PSNR graph for BPP

5. CONCLUSION

5.1 Ours Codec

An algorithm has been proposed to compress full-complex holograms by expanding the quantization tables to two. The algorithm utilizes two tables, each containing Qmax, Qmid, and Qbitdepth information per tile, enabling the selection of optimal values for each quantization block. This codec algorithm allows for finer quantization of Xmax in the quantization blocks by extending the quantization tables.

5.2 In the experimental results

The proposed codec algorithm has demonstrated improved compression performance based on the number of quantization tables used. Through analyzing the compression results of various holograms using CTC v9.0 Table 10, the general applicability of the proposed codec algorithm has been verified. A comparison with JPEG2000 and HEVC Intra results confirmed that the proposed codec algorithm contributes to enhanced compression performance.

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Real-time 3D holography based on AI for near-eye displays

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ABSTRACT

Holography is a promising approach for three-dimensional displays. Holographic displays have potential for next-generation VR and AR devices with pixel-level depth control, but problems such as requirement of high computational cost and are not sufficiently studied for realization of whole holographic system from the capture to display. Here, we introduce a real time holographic display system that captures, computes, and displays in real time. We also provide CGH optimization method with time-multiplexing to provide high-quality 3D hologram.

Keywords: Holography, Digital hologram, CGH, Near-eye displays

1. INTRODUCTION

Holography shows promise as a method for projecting and displaying three-dimensional (3D) images [1,2]. While holographic displays have the potential to enhance next-generation virtual reality (VR) and augmented reality (AR) devices by enabling true 3D projection, they still face challenges such as real-time computer-generated hologram (CGH) generation and display the CGH with high-quality. In this paper, we present an artificial intelligence (AI) based approach that addresses the aforementioned problems. The approach involves utilizing deep-learning techniques for 3D CGH generation, significantly reducing computational time. We have developed a real-time hologram projection system that can generate holograms in real-time from real-world scenes, incorporating real-time processing of capture, CGH generation, and display.

2. REAL-TIME 3D HOLOGRAPHIC NEAR-EYE DISPLAY

2.1 System architecture

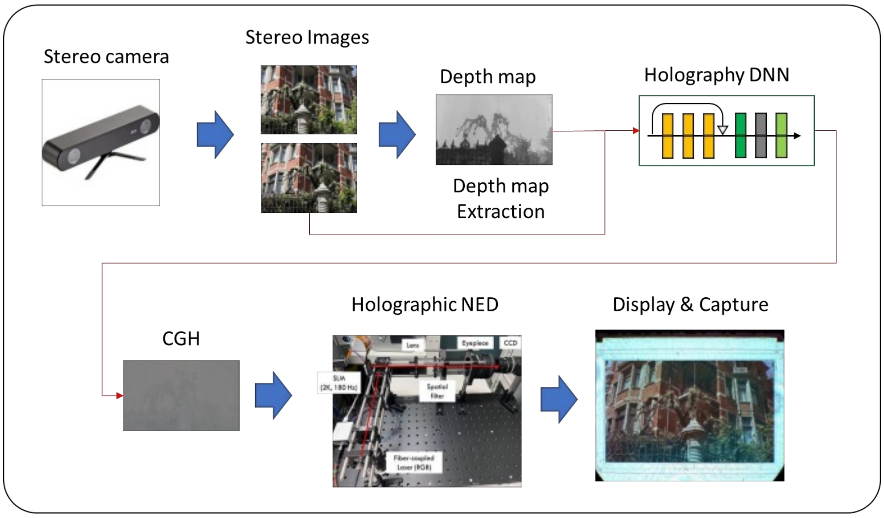

Figure 1. The pipeline of the proposed real-time 3D holographic near-eye display system. It consists of real-world scene capture, depthmap extraction, and CGH generation with deep neural network (DNN), and holographic near-eye display (NED) setup

We have developed a real-time 3D hologram projection system, as illustrated in Fig.1, which comprises real-world capture, depth information acquisition, 3D CGH generation, and holographic near-eye display (NED). To obtain real-world information, we utilize a stereo camera that captures binocular stereo images and provides real-time depth map images. Additionally, we have developed a deep neural network (DNN) for 3D CGH generation, which infers the complex amplitude (amplitude + phase) from an RGB and a depth image. The detailed explanation of the DNN will be provided in the next section. The resulting complex amplitude information is encoded into a phase image using a double-phase encoding strategy to meet the requirements of the phase-only spatial light modulator (SLM). For experimental demonstration, we have constructed a holographic NED prototype with a fiber-coupled RGB laser, a phase-only SLM, an optical system, and a CCD camera. Notably, color holographic display is achieved through time-sequential display.

2.2 Deep-leaning based CGH generation

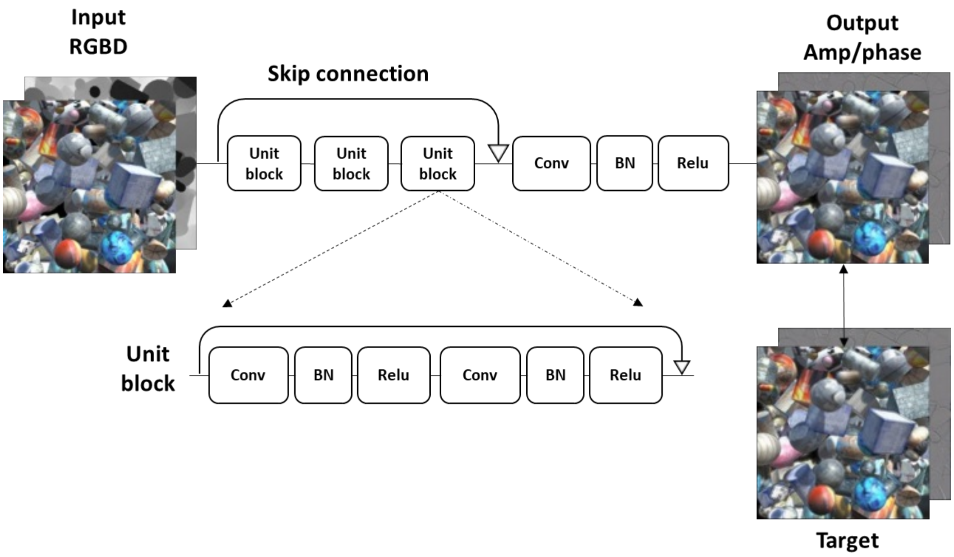

Figure 2. The structure of proposed DNN for generating 3D CGH. Here, we trained our network by supervised learning with pre-calculated target complex amplitude set.

In this section, we will present our DNN designed for generating 3D CGH. The architecture of our proposed DNN is depicted in Figure 2. We have adopted a recently published DNN called tensor holography [3], known for its ability to provide real-time 3D CGH with a lightweight network structure. The network comprises multiple sequential unit blocks that include two convolution layers, batch normalization layers, and ReLU activation layers with a short-cut. To train the network, we employed a layer-based multi-depth CGH generation technique to pre-render the target complex amplitude set. Each depth layer was numerically propagated from a distant depth to the foreground, with occlusion being masked. We pre-calculated a dataset of 1000 target samples and trained the DNN using a mean-square error loss function as supervised learning. Using our trained DNN, we can compute the complex amplitude at a resolution of 1920 x 1080 x 3 in just 20 ms, equivalent to a frame rate of 50 FPS. The computations were performed on an RTX 4090 GPU. Notably, the computational performance is 25 times faster compared to the numerical process employed for calculating the target set.

2.3 Real-time holographic projection results

Figure 3 is a screenshot of our real-time holographic projection system. The inset window on the right side showcases the RGB image captured by the stereo camera and its corresponding depth map achieved by the stereo RGB images. For this process, we utilize the ZED camera from Stereolabs. Since the ZED camera runs on the CPU, it takes additional time to uploading on GPU for apply the following DNN, which takes approximately 10 ms to generate a 1920 x 1080 x 3 RGBD image on GPU tensor form. To display the computed CGH tensor on the SLM, we have developed a direct CGH display module that utilizes the OpenGL library. By employing this module, our entire processing time, from capture to display, amounts to approximately 30 ms, achieving a frame rate of 33 FPS. The experimental results demonstrate that our proposed system can deliver nearly speckle-free and high-quality 3D color holograms in real-time.

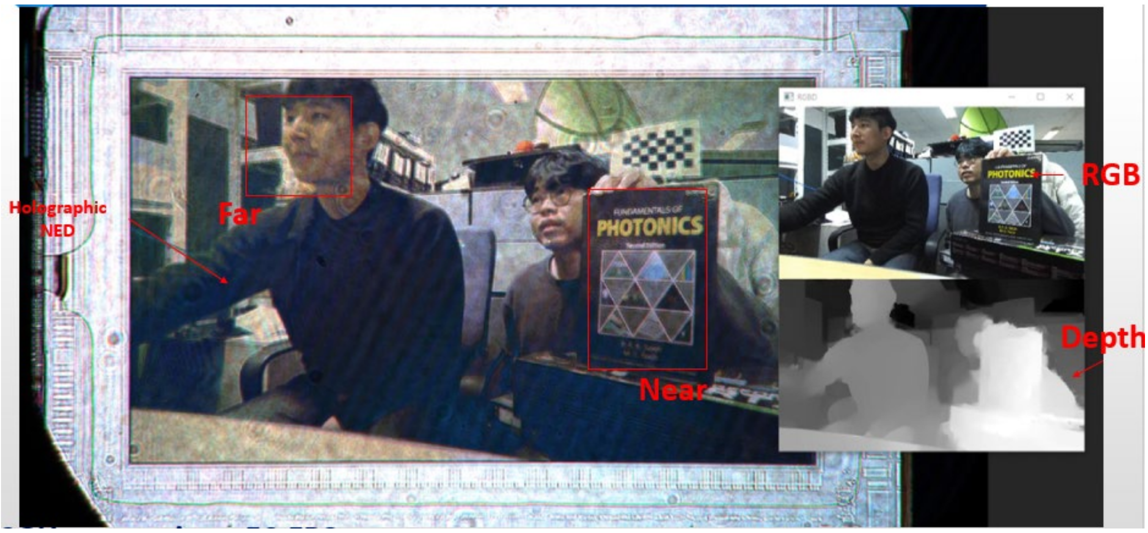

Figure 3. Experimentally captured holographic projection results using CCD camera. The RGB and Depth present real-world captured image and calculated depth map from the stereo-camera.

3. CONCLUSION

In this paper, we present a real-time 3D holographic projection system that offers high-quality 3D holograms with real-time capabilities. To enable real-time processing, we have developed an AI-supported CGH generation technology that significantly speeds up computation times, achieving a 25-fold improvement compared to conventional numerical 3D CGH generation methods. Additionally, we showcase a full-color holographic projection system that achieves a display frame rate exceeding 30 FPS at a resolution of 2K. We provide experimental demonstrations to validate the effectiveness of our proposed method.

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Full color incoherent holographic video camera with wide FOV

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ABSTRACT

We introduce a fully colorized holographic video camera with incoherent illumination. To acquire the fringe patterns under an incoherent light source, we utilize self-interference, which splits the incident light into two waves and interferes with each other. Our proposed holographic camera is configured using the geometric phase lens which is a polarization-selective optical device based on the nature of liquid crystal. Additionally, we analyze the resolution and field of view (FOV) and provide an experimental demonstration of the wide FOV real world holograms.

Keywords: Digital holography, holographic camera, incoherent hologram, video hologram, full color hologram

1. INTRODUCTION

Digital holography and holographic displays have been the focus of extensive research over the last few decades, owing to their potential to represent full three-dimensional (3D) perceptions. Constructing high quality holograms, rooted in wave optics, demand denser and more sophisticated optical modulation compared to conventional display panels. Advances in semiconductor and display technology have ushered in the pixel size reduction and conceptual implementation of fully colorized video holographic displays [1].

However, the practical application of these technologies presents several challenges. The field-of-view (FOV) in holographic displays is tied to the spatial-bandwidth products of the device, requiring the enlargement of the number of pixels to match the FOV of existing display systems. Moreover, this requirement substantially exceeds the data bandwidth at the holographic generation and transmission. Although the evolution of graphic processing units has facilitated the faster calculation of computer-generated holograms (CGHs), an increase in hologram resolution triggers a corresponding exponential surge in computational complexity.

In order to address these challenges, one solution lies in the direct acquisition of holography. Self-interference incoherent digital holography (SIDH) is a promising candidate which can record real-world holograms in incoherent illumination manners without safety issues from laser. SIDH operates on the principle of wavefront division and phase modulation. The incoming light wave is separated by the wavefront division unit and subjected to an optical path modulation. The phase modulation unit then eliminates bias and twin image noise using a phase-shift method [2]. Our group has introduced an incoherent holographic camera system implemented by a geometric phase (GP) lens [3]. The GP lens is a polarization-selective passive optical element that can simultaneously function as a wavefront division unit and phase modulation unit. Here, we analyze and demonstrate the FOV of our holographic camera system. Implementing a colorized polarized image sensor allows to establish a full-color incoherent video holographic camera system. The optical configuration influences the photographic characteristics of holograms. We demonstrate the response of FOV variation in terms of full color reconstruction.

2. METHOD

Figure 1 illustrates the recording schematic of a proposed incoherent holographic camera with simple configuration of GP lens and image sensor. The self-interference hologram is composed by the positive and negative spherical wave introduced by the GP lens. This Fresnel hologram can be expressed as a superposition of convolution with object intensity distribution I_s and point spread hologram (PSH) H_0:

$$H(x_s, y_s) = \iiint I_s(x_s, y_s, z_s) * H_0(x_0, y_0, z_0)\, dx_s dy_s dz_s \tag{1}$$

Therefore, the magnification of acquired hologram on image sensor plane can be derived by the relation between the distance of GP lens with object z_s and distance with image sensor z_h as shown in Fig 1

$$M_T = \frac{z_h}{z_s}. \tag{2}$$

In terms of viewing angle, FOV is calculated by the ratio of the distance with the GP lens and image sensor and the radius of the hologram r_h which is the same as the width of the image sensor

$$FOV = 2\tan\left(\frac{r_h}{z_h}\right). \tag{3}$$

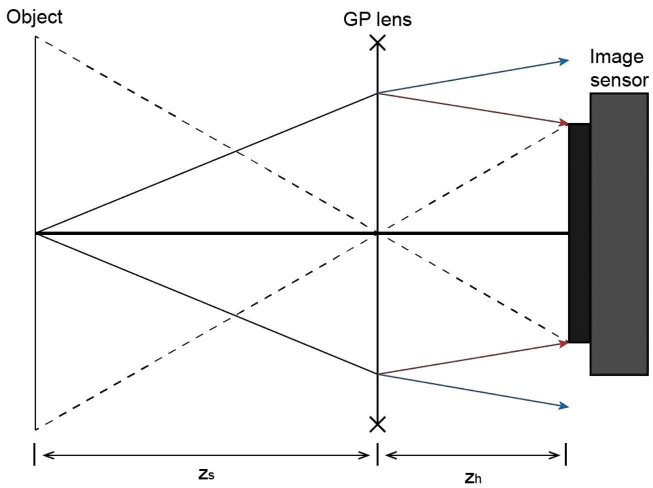

Figure . Schematic diagram of the GP-SIDH and geometric formulation of FOV

Note that the focal length of the GP lens does not affect the FOV. The optical power only affects the resolution of PSH and it can be interpreted to the reconstruction distance as follows

$$z_r = \frac{((z_s+z_h)f_{GP} - z_s z_h)((z_s+z_h)f_{GP} + z_s z_h)}{2z_s^2 f_{GP}} \tag{4}$$

where f is the absolute value of the focal length of the GP lens. As the optical power increases, the reconstruction distance shortens and is related to the enhancement of resolution. However, the pixel pitch of the image sensor restricts the maximum spatial frequency according to the sampling theory.

3. EXPERIMENTAL RESULT

To verify the reconstruction of the hologram according to the FOV variance, we capture the three different configurations of holographic cameras. The main difference of the distance with the GP lens and image sensor was tested at 4 mm, 8 mm, and 12 mm. The focal length of the GP lens is 275 mm at a green light wavelength of 525 nm and linearly proportional to the objective wavelength. The hologram, generated via a parallel-shifted phase shift method with the polarized image sensor, had a resolution of 1024 x 1024 pixels.

Figure 2 shows the numerical reconstruction of the full color hologram of a statue captured by our system. According to the aforementioned FOV equation, the FOV of each system configuration is 82°, 47°, and 32° respectively. An increase in the distance between the GP lens and the image sensor lead to a decrease in the FOV and increase in the magnification in reconstructed holograms as shown in Fig 2. However, as the FOV shrank, there is a noticeable increase in residual noise on the background, along with a chromatic shift towards red. Chromatic aberration can be attributed to the diffraction efficiency of the GP lens. When the system operates far from the designed reference wavelength, the phase modulation efficiency diminishes, leaving a residual bias.

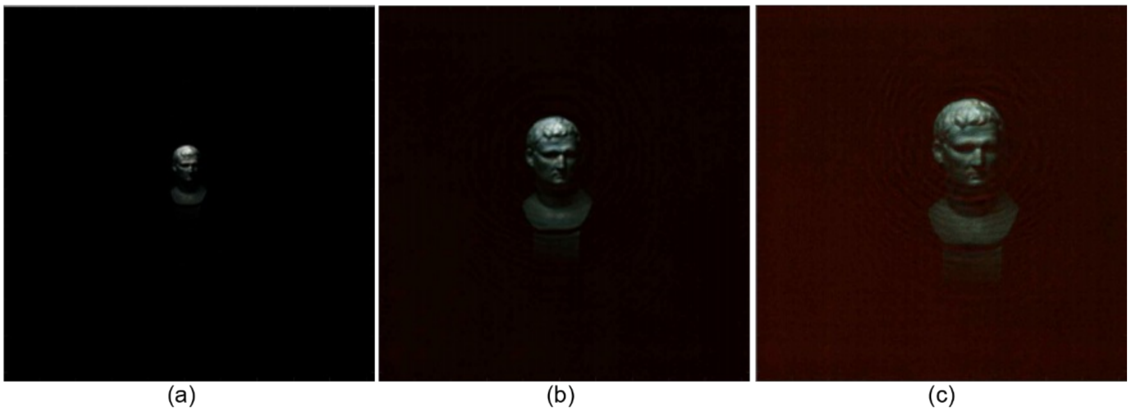

Figure 2. Full color reconstruction of GP-SIDH according to the FOV. (a) z_h = 4 mm, (b) 8 mm, (c) 12 mm (FOV = 82°, 47°, and 32° respectively).

4. CONCLUSION

In summary, we have conducted an analysis and demonstrated the FOV of an incoherent holographic camera. In terms of the generation of holographic data, a self-interference-based incoherent holographic camera can directly capture the complex hologram, utilizing the characteristic of the GP lens. The magnification of captured holograms is related to the system configuration, and to achieve the wide FOV holograms, parameter optimization is necessary. The acquisition of wide-view, real-world holograms with single shot can be synergized by combining with existing holography or computer vision techniques.

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Animated synthetic reality and next generation digital holography

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ABSTRACT

Imagine a raging wood fireplace that pops and crackles that is suddenly extinguished at a gesture of the hand. Or, an image of a human brain. A gesture by the presenter introduces the hard tissue (skull), with another gesture, the vascular data. Finally, a brain tumor is introduced to the 3D construct, timelapse animated to show it enlarging over a period of months. Using new techniques developed at Yves Gentet France) and a unique robotic LED system controlled using gesture recognition, developed at OCD University's PHASE Lab. (Toronto) This hybrid hologram display is hyper realistic and will find applications in 3D visualization including medical imaging.

Exploring the synergy of technological convergence: holography, AI, and ubiquitous computing

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Abstract

Converging technologies have opened the door to a new era of innovation, involving -Holographic technology

- AI -Light field technologies , -
- High powered ubiquitous computing systems.

Holographic AI combines the power of artificial intelligence (AI) with the capabilities of holography to create a new form of human computer interaction. The use of AI enabled holography will mean the creation of more natural and immersive environments, enabling individuals to interact with AI-powered systems in a three dimensional setting. This technology has the potential to revolutionize a wide range of industries, from healthcare to education and art & entertainment. With holographic AI, individuals can interact with virtual assistants and digital avatars in a more lifelike way, enabling more meaningful communication and interaction. The convergence of AI and holography also has significant implications for data visualization and analysis. Despite its many potential benefits, the development of holographic AI still faces numerous challenges, including the need for more advanced hardware and software, as well as overriding concerns: -data privacy -security. Ethical Considerations in the implementation of Artificial Intelligence, (particularly in the area of fine art production) Nevertheless, the potential benefits of this technology are significant, and it is likely to play a major role. in shaping the future of human computer interaction and AI. Given the Developments in these technologies in the past decade and with the knowledge that all things virtual and 3D have captured the interest and imagination of the public, we can speculate here on the future of synthetic reality and the role of holography, coherent light & optics in that future.

Keywords : Holography, Digital Holography, Tensor Holography, CNN (convolutional neural Networks), Hap tics, VR (virtual reality) AR (augmented reality) MR (mixed reality usually, AR and VR) XR any of the synthet ic realities(AR VR MR) Ubiquitous computing

1. Introduction

The convergence of emerging technologies will have ra significant influence of advances is digital holography. They include:Light Field displays,AI driven digital holographic image creation and storage,Advances in Mix Reality , Computational power of mobile devices, HapticsAdvances of these technologies is driven by large corporations and interest-driven research in Universities we the knowledge and resources to bring about rapid and significant change. Digital holography, as a technology is not the driving force, but a poor cousin who benefits from the evolution of these parallel technologies. Optimists, the author included, will agree that the whole of these technologies is greater than the sum of its parts.

2. State of the art displays.

Video in this section will examine dimensional displays including. Looking glass.

Figure 1. Looking Glass 65” 8K display up to 100 views.

53 Degrees horizontal and vertical. Limited sequence lengths.

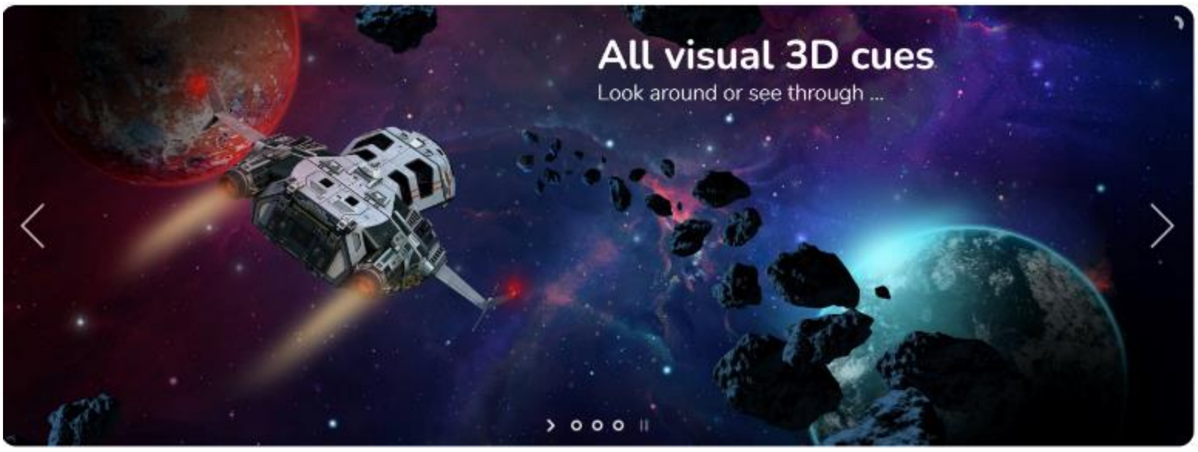

Figure 2. seareal

Claims:
- True interference-based holographic reconstructions in 3D space
- Deploys to multiple platforms
- Suggests laser illumination
- Hints at edge illumination,
- Eye tracking and fovated rendering. (Sub Holograms)

It will also speak to the state of MR including the new release from Apple “Vision Pro

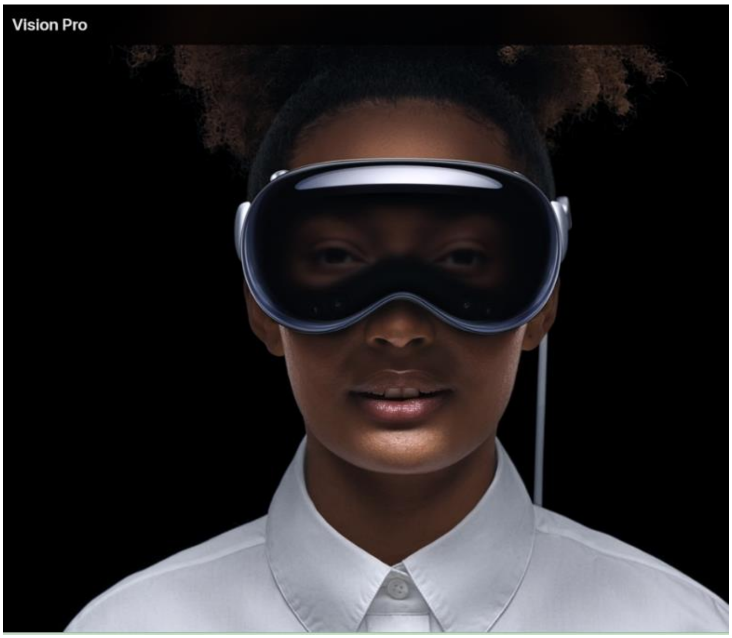

Figure 3 . Mixed Reality(almost), Integrates all of Apple's existing technologies, AI voice-activated and gesture-recognition. Exploits M2 graphics engine. Is heavy, expensive and has a creepy electronically generated view of the user's eyes.

3. The problem with VR/MR

Why has VR not been widely adopted as predicted:

A. A one person experience/ The film industry has not successfully commodified VR

B. Distribution/ Enormous Amounts of Data required

C. VR sickness/ Latency/ Eye strain/Fatigue/Accommodation

All of these problems are being solved in tandem.

Accommodation is one of many visual cues to the brain that suggest to humans that the images they are witnessing ae real. It has to do with the muscularity in our eye that suggests that an object is, for example 2 metres away. When we see this object through the lens of an HMD (head mounted display) placed only a few centimeters away, this conflict can contribute to "VR sickness, one of the reasons that some student drop out of courses that teach XR. This "lack of accommodation", often seems to effect those individuals with high visual acuity. (artists) . Light field displays will not only solve this problem by creating the necessary depth cues, but will also be able to replace the need for prescription glasses when used for XR. Tensor Holography Data storage and transmission. The process invented at MIT uses convolutional neural networks to teach the computer the physics required to generate the holographic scene. This will not only shorten the otherwise near impossible task of real-time digital image creation. It dramatically reduces files size, and converts the task to functions that are readily performed by processors in mobile devices.

Distribution on the web and mobile devices. AI and proliferation of low cost SLMs will lower the cost of holographic technology drop significantly. In tems of:

- Bandwidth required

- Computational resources

- Economically

4. Content-creation Past/Present/Future

This section shows some historical techniques and processes used in content creation for holographyThe or doing things the hard wayHypercube 1986

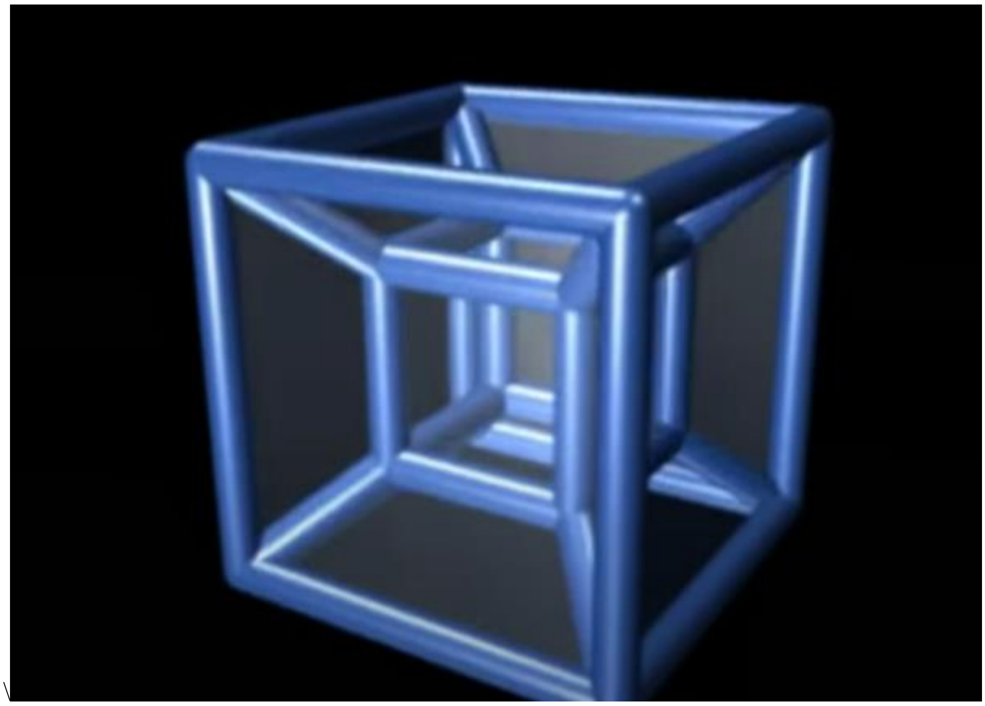

Figure 4. An image of a 4 dimensional Hypercube.

Show video of frame by frame generation of animation for early computer generated holography
The Easy way.. CGI
Download the hypercube animated model from SketchFab

Queen’s Park June 23, 1983

Shows video of footage recorded on film via helicopter with westcam mounted film camera
And the same project today
Recorded using a film industry drone.

Figure 5. DJI’s latest cinema drone flies 8K full-frame gimbal camera

Working with found objects

Student work from 2nd year undergrad XR class. Current tools for hyper-real content creation: Show video, Unreal’s Meta Human, Show video

5. AI in content creation

This section talks about the use of AI in content creation , How the hologram “Choose your own adventure” was produced Prompts Used for AI generation: The Plot/The Characters/The Name of the Disease. Video showing the use of Photogrammetry to crate the dead women segment. Video list found objects in the composition.

6. Conclusions

Emerging technologies will converge on and transform the world of digital holography. Easy to use digital tools for content creation may become the mainstay for artist who wish to exploit the medium. The potential for Ubiquitous computing and web transmission of digital holographic images is here (almost)

Slide: Ubiquitous computing (or "ubicomp") is a concept in software engineering, hardware engineering and computer science where computing is made to appear anytime and everywhere. In contrast to desktop computing, ubiquitous computing can occur mobile devices, for example.
The Future:
Filmmaker/Production Designer Phillip Barker’s Vision
Show Video

Further discussion:
Ethical aspects of AI content creation.
Potential use and abuse of the technology

TRACK 4.

History, Culture, and Education

Holography, serendipity & me: the ups and downs of 75 years

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ABSTRACT

This paper reviews the history of display holography since my own involvement started in 1977. It sets out the history of commercial decorative display holograms. Then it recounts the events which led to the bankruptcy of the Museum of Holography in New York and how this was part of a pattern affecting most specialist holography museums. The paper closes with observations about the past, present and future of display holography.

Keywords: Display holography, art holography, holographic industry, Light Fantastic, Museum of Holography, Light Dimensions, Ian Lancaster

1. INTRODUCTION

There were two events in 1948 that were to have a signification impact on my life: the first was Denis Gabor's lecture to the Royal Society in London announcing his invention of holography; the other – I was born! I don't know whether it is coincidence, karma or serendipity that holography and I are the same age, but we have certainly had major interaction as we both matured.

As it happens, I don't remember either of those 1948 events, but the serendipitous nature of the first – Gabor's discovery of holography while he was, in fact, trying to find a way to improve the images of electron microscopy – set the pattern for my career some 30 years later. Serendipity became a pattern for me in a life that has had its ups and downs. As, indeed, has holography.

In this paper I will explain how my path has intersected with and been affected by holography. I will set out some of the ups and downs of display holography (unfortunately, more downs than ups), concluding with a discussion of where display holography is now and what the future might hold for it.

2. THE EARLY YEARS

The first time I came across the words "holography" and "hologram" was in a science news item in The Guardian newspaper in the mid-1960s. This article was reporting the Leith/Upatnieks invention of off-axis holography, which was another example of the serendipity of holography, given that they were researching synthetic aperture radar (SAR) to improve radar imaging. The article caught my eye because I was at the time a budding amateur photographer and an avid reader of science fiction. So the idea of three-dimensional (3D) photographs really appealed to me.

But that did not define my early career. How could it when there was no path into holography? Instead, I came away from university with a degree in Drama and American Studies, which led me to a career in arts administration.

From 1973 to 1977 I worked at the East Midlands Arts Association (EMAA), based in Loughborough, England, so I lived about a mile from Nick Philipps lab at Loughborough University. Not that I knew it at the time, although maybe there was some osmotic infusion of holography into my blood stream. I first saw Nick's work at the 1977 Holoco *Light Fantastic* exhibition at London's Royal Academy of Arts when I queued in the rain for my first viewing of holograms. Needless to say, I was fascinated, intrigued, entranced … and hooked.

An experience shared by many people in this room, I'm sure, on their first viewing of a display hologram.

Then I was appointed as the Arts Director at the Calouste Gulbenkian Foundation's UK branch, so I went to the second Light Fantastic exhibition in 1978[1], but this time, I was a guest at the opening reception. What a difference a year can make!

So it was that I first met members of the young UK holography community. Nick Philips of course, and others on his Loughborough and Holoco team, as well as Margaret Benyon, John Brown, Jeff Blyth, Jonathon Ross and Edwina Orr.

Now, not only was I hooked, but I was in a position to help this young creative holography community. The Gulbenkian Foundation was committed to directly supporting artists, so I established a fellowship for artists working in holography (alongside schemes for musicians and video artists). But where could budding British holography artists find somewhere to make their work? A fortunate few – very few – had built their own holographic studios (the trailblazer being Margaret Benyon), or had access to a university or college lab. Most aspiring holo-artists, though, could only dream of having their own studio.

2.1 The Goldsmiths' holography studio

So serendipity again had a role… as three things came together to make possible *my* dream of establishing an open-access holographic studio for artists.

Firstly, the Gulbenkian Foundation was forward-looking and innovative, *and* had a close relationship with Dr Richard Hoggart[2], the then Warden (i.e. Principal) of Goldsmiths' College in New Cross, London. Goldsmiths' was – and is – renowned for its arts programmes.

Secondly, while I was at the EMAA I'd heard of a programme funded by the Rockefeller Foundation to encourage overseas tours by American modern dance companies which focused on a country's regions, not its capital city. So I'd got involved and met Howard Klein, my opposite number as Arts Director at Rockefeller, who also was a holography enthusiast.

Thirdly, that in turn got me connected to the Cultural Attaché at the US Embassy in London, which put me on a State Department fellowship programme to tour the USA researching the country's tech-based arts scene. Needless to say, I used that opportunity to meet American holographers from coast to coast, visiting their studios, learning from them how to build an isolation table and being stunned by the quality of the holo art I was seeing. On this trip I also made my first visit to the Museum of Holography in New York, to the Chicago Museum of Holography, to the MIT Media Lab, and to the Holos Gallery in San Francisco.

So with Gulbenkian money for equipment, in space provided by Goldsmiths' College, with support from the Rockefeller Foundation to fund Michael Wenyon as course leader, we built a holography studio for artists which opened in May 1980 Mike designed it and ran it, with Susan Gamble, offering introductory and advanced courses in display holography. To quote Jonathan Ross, "During the 1980s, the holographic art scene in the UK, where I live, began to develop, fostered by the workshops run by Michael Wenyon and Susan Gamble at Goldsmiths College…"[1]. We also managed to bring over other artists from the USA, including Rick Silberman and Bill Molteni, to work at and run master classes at this studio.

The Arts Council of Great Britain stepped in to offer bursaries to artists to attend courses and work at the studio, enabling Bill Culbert, Peter Donebauer, Liliane Lijn and Andrew Logan to learn and make holograms there. In 1982, Wenyon and Gamble organised a show of the holograms produced at the studio between 1980 and 1982, which toured the UK.

(Of course, it was entirely appropriate that I enrolled on Michael's first course, to ensure that the Foundations' money was being well-spent… and so that was where I made my first hologram, processed in what Mike told us was "van Renesse A and B" solutions; more serendipity: my first connection with Rudolf van Renesse, who was to become a close collaborator and friend in the optical security field – but that's another story.)

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[1] It was unprecedented for the Royal Academy to repeat an exhibition, but the first Light Fantastic was so successful, with so many people not able to get in, that the Academy invited Nick and his team back the following year.

[2] Richard Hoggart was a hero of mine, having read his *The Uses of Literacy*, a seminal book on the value of popular culture, in my teens. He'd then been the Assistant Director General of UNESCO before becoming Warden of Goldsmiths in 1976. I was starstruck!

3. FROM ARTS ADMINISTRATOR TO HOLOGRAM ENTREPRENEUR

After five years at the Gulbenkian Foundation it was time to move on[3]. Holography had me well and truly hooked, so I moved from a fabulous, well-paid, influential, secure job as an arts administrator to be the barely-paid founder of a company making decorative display holograms on Agfa's silver halide holographic film. I established Third Dimension Ltd (TDL) with a £50 overdraft from a supportive bank manager and Jeff Blyth as holographer.

By now there was a Light Fantastic gallery in London's Covent Garden, set up by Peter Woodd, who had been associated with Holoco, and Hamish Shearer had opened Parallax, a shop selling light-effect and optical novelties in Covent Garden Both became key early customers. But a watershed in the company's survival was the *Light Dimensions* exhibition, first at the Royal Photographic Society's gallery in Bath, then at the Science Museum in London. Mounted by Eve Ritscher, this hugely popular exhibition had a gift shop – of course – run by John Brown of Light Impressions Europe Ltd, where we sold a lot of holograms. Mainly 4" x 5", with some 8" x 5 and 10" x 8" film reflection holograms. See section 6 for more on Light Dimensions.

Serendipity played its role again… TDL was initially working out of a small start-up space in what are now called incubator units, in Greenford, an outer London borough. The local weekly newspaper ran an article on this incubator, naturally featuring the young hologram company on the site. The next day a tall fellow banged on our door, telling me he had to come and work for us. He had just returned from a couple of years in Brazil, was staying with his mum in Greenford, had known about holograms and wanted to make them. So reading that article felt like karma to him. I declined his request to join this – at the time – two-person company; we didn't need a third person, particularly someone who would need training, and we certainly couldn't afford a third person. But he was back a couple of days later, insisting he wanted to work with us, no pay to start with. Even then I turned him away. Yet he came back, so the third time I relented – after all, we'd just won our first large order. He was a quick learner and a hard worker.

That was Mike Medora, subsequently founder of Colour Holographic, now TrueLife Optics, and one of the best creators of colour display holograms in the world.

After about a year we moved into a bigger unit in Cricklewood, NW London, where we needed another holographer to lead the mastering and production. Jeff is a brilliant holographer with an excellent grasp of photosensitive chemistry, but he was not a team leader. We advertised and interviewed a young chap who had just returned from a period as a researcher in optics at the Rochester Institute of Technology in upstate New York. So we hired him: Dr Paul Dunn, an inspired choice as our senior holographer (as Applied Holographics, later OpSec, was to find when he joined that company). Paul, by the way, is now the Chairman of the International Hologram Manufacturers' Association.

In 1988, after I'd left TDL (see below), Martin Richardson was appointed as the Creative Development Manager on his graduation from the Royal College of Arts postgraduate holography course. He stayed with the company, through its rescue from bankruptcy by John Brown, who then sold the assets to Martin. The Third Dimension brand continued on silver halide reflection holograms until Agfa stopped making this material in 1993.

So by accident or design – serendipitously – TDL gave a first commercial holography job to three people who have subsequently made significant contributions to display holography.

TDL's strategy was to produce reflection silver halide holograms on film that would appeal to retailers and their customers. We introduced new images twice a year and eventually had a catalogue of almost 100 holograms, produced four-up, two-up or one-up on 8" x 10" film. We produced these holograms on Jeff Blyth's contact copy jig, of which there were several on each isolation table.

Once we were established I approached some of the British artists to produce licensed editions of their work; one of the first to agree was Adrian Lines, who's *Mirror Man* became a best seller. His tragic early death robbed us of an artist who truly understood the medium of holography – fig 1.

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[3] In *Holographic Visions* Sean F Johnston states that I was "administrator" at the Gulbenkian Foundation in Britain for a decade, one of several inaccuracies in this interesting book. To add insult to injury, in describing how the Goldsmiths' studio was established he totally ignores its genesis at the Gulbenkian Foundation and that organisation's significant funding of it, through my role as Arts Director.

Fig 1: Adrian Lines' *Mirror Man*, a 5" x 4" film edition (Photo courtesy of Jonathan Ross)

We also made many promotional holograms for corporate trade shows or for display at headquarters, most of which were 30 x 40 cm holograms.

TDL was successful, despite Sean Johnston's dismissive comment in *Holographic Visions*[2]. Over the four years I led the company we grew global annual sales to around a profitable £500,000 (roughly equivalent to £1.5m today). I left the company after a disagreement with my then business partner about the future direction of the business. I don't think there are any formal records to prove this, but over 11 years probably more film reflection holograms were made – and sold![4]

Figure 2: The Third Dimension retail display unit

[4] In *Holographic Visions* Sean F Johnston writes that "(Third Dimensions') return from sales proved unsustainable." Another inaccuracy: Third Dimension was profitable; the company was mismanaged into bankruptcy after I left but the fact that the brand continued under different owners demonstrates that it was making money.

– under the Third Dimension brand than from any other producer. Certainly the company was Agfa's best customer for its HoloTest film – just not good enough to keep the production lines running beyond 1993.

But the challenge of getting holograms displayed well in shops taught me one key thing about display holograms: *they need to be properly lit to be effective as decorative or promotional items*. With a specialist company we designed a display unit with integrated halogen spotlight, which boosted our sales significantly – although looking back on it I now think it was an ugly, intrusive unit and we probably could have done much better.

4. AND SO TO NEW YORK

In autumn (fall) of 1986 I was asked to become the Executive Director (ED) of the Museum of Holography (MOH) in New York. The powers-that-be there were attracted by my having worked in the public arts sector and run a successful display holography company. In other words, I understood both holography and the subsidised sector.

Here I must acknowledge the support of the late Walter Clarke, of Global Images. He was a huge but quiet supporter of art holographers and contributed to the costs of my appointment.

I started at the Museum in October 1986 and – though I say it myself – my first year was one of the most successful in the Museum's first 11 years, financially and in the number of people viewing holograms. Unfortunately, that proved to be misleading.

In my first weeks in the job I had to prepare two major applications: to the Institute of Museums (the Federal Agency for museum funding), and – unusually – to FAO Schwarz, the famous American toy shop, that was moving from its prime location on the corner of Fifth Avenue and 58the Street but didn't want this store to be empty over the Christmas period. Through its PR agency, FAO had invited a handful of organisations to submit proposals for the use of this prime space and we were selected!

The amazing MOH creative team then had about a month to design, construct and install an exhibition in this very well-positioned space. Because of the very tight timetable we took *Alice Through the Looking Glass* as the theme, displaying holograms in-store and in the windows[5]. There are no records of how many people came in through the doors (never mind those who stopped to look in the windows), but Barclay Thompson, of A.H. Prismatic, which had the franchise to operate the Museum's gift shop, has said that the company took over $240,000 at the FAO exhibition – its most successful outlet and several times the annual revenue from the Museum's shop[3]. And of course the Museum received a percentage of those sales.

As the New York Times wrote: "The majority of visitors to the Museum of Holography-Fifth Avenue, seem to perceive holograms as objects of amazement and amusement."[4]

Serendipity again! Simply an example of being in the right place at the right time and putting together a persuasive case for the MOH to fill this otherwise empty space in the vital Christmas season.

Meantime, the application to the Museums' Institute was going through its bureaucratic process and we were eventually awarded the largest public sector grant in the Museum's history.

When I became the ED at the Museum there was no future exhibition programme and no staff curator. So we quickly put together the programme for the coming year, and thanks to Linda Law, who we asked to curate a show drawing on works in the Museum's collection as the first new exhibition, we had a new show which opened early in 1987.

The most ambitious exhibition in this new programme was *The Holographic Instant,* showing pulse laser holography. That was curated by Marcia Merryman-Means, who became very worried after her first couple of months' research that there was little pulse laser holography to show; I reassured her that there was much activity in Europe, which we'd planned for her to visit, and sure enough after that trip she had more than enough material to mount an impressive and informative exhibition.

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[5] I believe this was the second time that holograms had been seen in Fifth Avenue windows, the first, of course, being the famous Cartier hologram of a woman's hand draped in jewellery, made by McDonnell Douglas in 1972.

The event included the installation of a pulse laser studio in the Museum’s basement, thanks to the generous donation of a laser by JK Lasers and the knowledge and creativity of Ana-Maria Nicholson, who designed and operated the studio. She made portraits of several notable New Yorkers in that studio, and when the studio was dismantled I believe she became the proprietor of the pulse laser, ensuring that it was well-used.

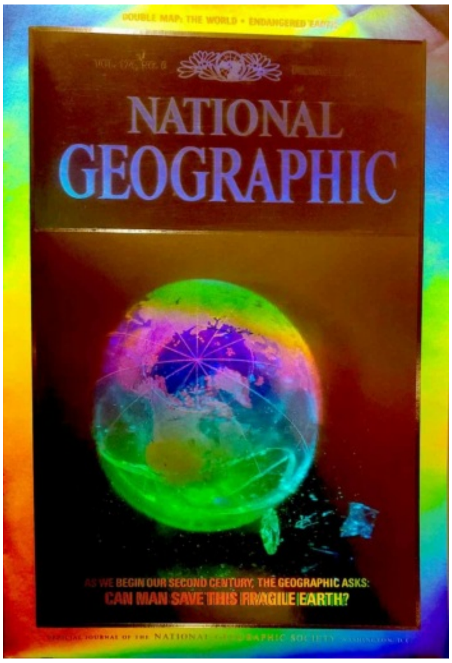

Figure 3: National Geographic, December 1988, the holographic cover, inspired by the MOH's *Holographic Instant* exhibition.

The exhibition certainly impressed the National Geographic Society, which put a bullet through a very expensive specially commissioned Steuben glass globe, recording this with a pulse laser for its third holographic cover. The issue contained an explanatory article explaining how the cover was made, naming only American Bank Note Holographics, where it was embossed from a pulse laser master made under leadership of Ken Haines. Sadly, this article did not credit the Museum for the inspiration, despite it having its genesis in a meeting I had with Gilbert Grosvenor, President of the Society.

4.1 Reality Hits

Unfortunately, those successes gave me – and others – a misleading impression of the state of the Museum. For its first ten years (we celebrated its tenth anniversary in fall, 1986) its finances had been precarious (A H Prismatic took over the shop because it was owed a large sum for the supply of holograms and this was the Museum’s solution to avoid having to pay the debt), but the FAO Schwarz success and, more particularly, the large Museums’ Institute grant, suggested that we were turning a corner. Sadly, this was a false dawn.

That was brought home to me when our application to the Museums’ Institute the following year was turned down. The reason given was that we did not have the visitor numbers to justify a federal grant, while the previous year’s grant had been an attempt to give the Museum an injection to support the programme of the new director.

I looked into the situation of New York City’s museums, the mega-institutions but also the smaller, specialist museums and reached an unfortunate conclusion:

The Museum of Holography was in the wrong place.

At the southern end of Mercer Street, near the corner with Canal Street, in what was becoming known as the up-and-coming area of South of Houston Street, or SoHo, this location was off the beaten track for museum visitors – locals and tourists alike. Although it is true that SoHo was becoming a trendy, fashionable area, it is mainly visited by locals looking for contemporary fashion or trendy dining; it is not a destination area for museumgoers and tourists; indeed, you could count the number of people walking along that part of Mercer Street on any given afternoon on two hands.

So the MOH's visitor numbers compared badly with those of other specialist museums in uptown Manhattan, or near to the ferry terminal at southern tip of the island. This was a worry for the long-term future of the Museum.

Then the landlord – who had also been persuaded that the area was becoming a magnet for fashionistas – gave notice that he would be ramping up the rent over the next few years. They knew we could barely afford the bargain rent that had been negotiated when Mercer Street was full of workshops and warehouses, so it was clear that they wanted the Museum out so they could charge an exorbitant rent to a clothing shop or art gallery.

How could the MOH survive this pincer movement?

4.2 A radical survival proposal

My proposed answer to that question was radical, too radical, it turned out, for the Museum Board.

That proposal was a four-part plan:

1. Close the Mercer Street premises, saving the huge overhead that entailed;
2. Continue the very successful programme of touring exhibitions, the magazine publishing (*Holosphere*) and an (admittedly reduced) education programme;
3. Find new premises in a more appropriate part of the city, ideally through negotiation with the authorities to be offered empty premises in the right location;
4. Use the breathing period between closing Mercer Street premises and opening elsewhere – which could have been anything from two to several years – to run a capital and endowment fundraising campaign for the money to ensure the viability of the Museum of Holography in these new premises.

Regarding that last point: New York was then the epicentre of a thriving commercial hologram industry. American Bank Note Holographics (then one of the most successful hologram producers in the world), Crown Roll Leaf, Transfer Print Foils, Coburn Corporation, HoloPak Technologies, Bridgestone Graphic Technologies, and others were all within striking distance of the city. There were other successful companies in Pennsylvania and Massachusetts within a couple of hours of NYC. I spoke to most of those companies and all were enthused at my "hypothetical" proposal for them to commit capital and long-term support to a re-located museum.

There was actually a – serendipitous – fifth part to the plan. The Regal Press, a forward-looking Boston-based printing and packaging company, had just started working with embossed holographic material and wanted to make its mark in the holographic world. Bill Duffey, the founder, contacted me to explore the possibility of sponsoring an exhibition in their city. Of course, I jumped at this possibility, and it turned out that they had a large downtown store available (shades of FAO Schwarz). Could this be a temporary home for the Museum's exhibitions?

I put this plan to the Museum Board, pointing out that there would be no Museum within three years unless such a radical plan was adopted. Unfortunately I didn't prepare the ground or make my case strongly enough; one Board member supported me – Stephen Benton, whom I had invited to join the Board soon after becoming ED. I badly underestimated the loyalty to both New York and the Mercer Street premises of the other Board members, who were all of New York and most of whom had been on the Board for all of the Museum's 11 years. They were shocked and affronted at the idea of closing the Museum's physical presence in NYC, so didn't accept this proposal.

In January 1987, barely three months into my position as ED, at the second Practical Holography conference, part of SPIE's Photonics West Symposium, attended by around 200 delegates, I'd given a paper about my plans and aspirations for the MOH. In response to a question from a delegate, I stated that it was not my intention to lead the Museum into bankruptcy. I hadn't changed my position in the ensuing 18 months, so I gave the Board my resignation on the grounds that I would not stay to oversee the Museum's bankruptcy within three years.

I was disappointed that the Board rejected my proposal (nor did it even consider exploring other radical ideas to preserve the Museum); I was disappointed in myself that I hadn't persuaded them of the need for radical action; and ultimately I was most disappointed at the accuracy of my forecast that the Museum would close within three years.

But at least Steve Benton was able to effect the rescue of the collection by the MIT Museum. It's ironic that it is now housed in Cambridge, Mass, across the Charles River from the downtown Boston location that might have housed it temporarily.

5. BACK TO LONDON

So I returned to London as European editor of *Holography News®* (HN), becoming editor within a couple of months.

Reconnaissance Holographics, Lew Kontnik's company and TDL's former North American distributor, had started HN in 1987. In the six months between walking away from TDL and joining the MOH, I'd had the idea for a business newsletter for the nascent holography industry, but I couldn't pursue this when I was at the Museum, which published *Holosphere,* its quarterly (more accurately by 1986, occasional) magazine. So I suggested the idea to Lew… and when I was back in London I became an equal partner in Reconnaissance Holographics, taking over as editor with Lew as American editor, given that he had another full-time job.

Within a few years the predominant topic in HN was security holograms – embossed, tiny, hot-stamped onto credit cards, brand labels and eventually banknotes. There was very little news about display holograms to report. This led us to launch a second newsletter, *Authentication News®*, partly prompted by a discussion with Richard Bard, the Denver-based founder of the company that became OpSec. Serendipity again; Lew had moved to Denver to run the University's incubator site. We changed the company name from Reconnaissance Holographics to Reconnaissance International, moving the focus more and more to authentication and anti-counterfeiting.

In the meantime, though, Reconnaissance launched the Holo-pack•Holo-print® conference (initially with PIRA, the Print Industry Research Association; now The Holography Conference), orchestrated the founding of the International Hologram Manufacturers' Association (IHMA) and launched another five B2B (business-to-business) newsletters and associated conferences.

I "retired" from Reconnaissance in 2015, having edited HN for 25 years, been the General Secretary of the IHMA for 23 years and researched and written four reports on the holography industry and markets[5] as well as editing and compiling two editions of the *Holo-pack•Holo-print Guidebook*. Thus I had an objective overview of global holography and became something of a commentator on the field.

Notwithstanding the predominant coverage of the security and packaging side of holography, I made sure that HN continued to cover display holography. That included an interview with Yuri Denisyuk, in which he told me that his inspiration to explore "3D photography" had been a science fiction story in which visitors to a derelict planet discover a 3D photograph in the ruins. I felt a thrill of recognition that this giant of holographic invention and I shared the same inspiration!

6. OBSERVATIONS ON DISPLAY HOLOGRAPHY

In the past 43 years I've made one-off reflection holograms, supported artists working in the medium, established and successfully run a company making reflection holograms on silver halide film (and selling them all over the world), run what was probably the world's leading holography museum, edited the only surviving regular English-language publication on holography, led the industry association – and continued to be fascinated, absorbed and hooked by the visual medium that is holography.

So what do I make of the subject of this International Symposium – display holography?

6.1 History

Despite my reservations about *Holographic Visions*, it gives a comprehensive history of holography to 2006, so I'm not repeating that history, but I simply highlight a few key factors in the development and presentation of display holography – with credit to that book for prompting or confirming certain memories. This is not a comprehensive list, more an impressionistic view of what was happening.

Training and education: Through the 1970s and into the 1980s many holography studios offered hands-on courses; that at Goldsmiths' College was not a trailblazer, rather it followed the pattern set by the San Francisco and New York Schools of Holography, Lake Forest College and others, mainly in the USA. Other studios offering hands-on courses included L'Atelier Holographique in Paris, Richmond Holographic Studios (London) and Ideecentrum in the Netherlands. These courses gave many creative holographers their first experience, setting them on a lifetime – or at least a decade or two's – path.

These informal courses were followed by more formal educational opportunities for artists at institutions such a London's Royal College of Art and Goldsmiths (naturally!); at MIT's Center for Advanced Visual Studies; the School of the Art Institute of Chicago; St Mary's College, Indiana; the Academy for Media Arts in Cologne; Sydney College of the Arts and the University of Tsukuba, Tokyo.

Galleries and museums: Similarly at this time there were numerous permanent venues for the public to see holograms. There were retail galleries: Holos in San Francisco and at least half-a-dozen others across North America; Third Eye in Paris; The Hologram Place in London (followed by the two in Covent Garden mentioned above); Matthias Lauk's outlet in Cologne, as well as Genoa, a gallery in Tokyo.

These commercial, mainly owner-run outlets, operated alongside a growing number of holography museums or more ambitious educational centres, such as those in New York, Chicago, Paris and Cologne.

These venues gave exhibit opportunities for artists working in the medium, although some adventurous non-specialist galleries had also hosted one-person shows, for example Margaret Benyon's exhibition at Nottingham University art gallery (her home town). Additionally, as display holography slowly became accepted as a legitimate artists' medium, established museums and galleries took it on board, through exhibitions and acquisitions, including Britain's Victoria & Albert Museum, several municipal art museums in Germany and the Smithsonian in the USA.

Blockbuster exhibitions: Which naturally leads me to mention the blockbuster exhibitions of the 1970s and 80s. In 1975 Posy Jackson and Jody Burns mounted *Holography: the First Decade* at the International Center for Photography in New York (leading them to found the Museum a year later), which attracted crowds and lit the blue touch paper for a series of overview exhibitions around the world. That same year there was an exhibition at the Seibo Museum of Art in Tokyo, which Fujio Iwata has described as "the opening of the holographic era in Japan".[6]

I've mentioned Eve Ritscher's 1983 *Light Dimensions*, which attracted hundreds of thousands of people in Bath and London, but there were similar mega-shows, or blockbuster exhibitions around the world, all attracting six-figure attendance: *Licht-Blicke* in Frankfurt, *Alice in the World* in Tokyo, *Images in Time & Space* in Montreal[6] and others.

These shows meant that display holography was in the public eye, getting significant media coverage on top of the exposure to those who were lucky enough to visit.

Meetings: One indicator of the vitality of the creative holography community was the number of meetings arranged for them. In the late 1960s and early '70s there had been several conferences for holographic scientists and engineers, but the 80s saw the introduction of meetings for a wider constituency of holographers. In 1981 Tung Jeong organised the first International Symposium on Display Holography at Lake Forest College, Illinois; SPIE added Practical Holography to its Photonics West symposium in Los Angeles in 1986, then included holography in several of its non-US meetings, including those in The Hague, Prague and Tokyo.

There were also many smaller, more informal meetings organised by national or regional holography organisations, e.g. Britain's Royal Photographic Society's Holography section; HODIC (the Holographic Display Engineers and Artists Group) in Japan and groupings in San Francisco and New York City.

Material supply: While many creative holographers found the benefit of using self-prepared dichromated gelatine (DCG) as their photosensitive medium of choice, the lure of a potential large new market for an imaging medium attracted leading photographic materials producers to invest in developing holographic emulsions, coated initially onto glass (an obviously stable carrier for holographic exposure), then film, as practitioners found ways to hold it stable. Thus Eastman Kodak, Agfa, Ilford and Fuji became suppliers of silver halide emulsions sensitised for holography. The affordable availability of recording materials facilitated the emergence of individual and small company hologram producers (TDL being the obvious example for me to refer to, but we eventually had half-a-dozen competitors around the world).

Additionally, excellent high-resolution silver halide holographic emulsions were made by Slavich in Russia, but these weren't readily available outside the country until the post-Glasnost era.

Photopolymer was under development as a holographic medium at DuPont in the US and Dai Nippon in Japan, but it was not yet easily available.

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[6] Disclosure: As ED at the MOH I contributed to the curating of this exhibition.

Summary: These various factors facilitated, supported and even encouraged the growth of display holography through the 1970s, 80s and in to the 90s. There was a feeling of community offering mutual support and encouragement. But if we look at these factors now…:

6.2 The present

Training and education: Where can an aspirational display holographer learn their craft now? The number of informal courses offered by practising holographers has dropped dramatically, as has the number of more formal courses. The HoloCenter in New York, now led by Linda Law, continues the strong New York-area commitment to artists and holography, while Iñaki Beguiristain offers a range of one-to-one courses at his studio in Essex, England, as does The Holography Studio in Amsterdam, The Netherlands.

Also in the UK, De Montford University offers postgraduate holography, while Ohio State University (USA) and the Technical High School Cologne offer holography as an option in their physics or related courses (the former with a pulse laser holography studio, where it offers courses and residencies in association with the HoloCenter). But there are few other formal or informal courses available in the Americas or Europe. I confess that I'm not in touch now with what's happening in Asia, but I am aware that there has been a remarkable interest in holography at universities and some corporations in South Korea (which is, of course, why we are here at ISDH this year).

Goldsmiths' College dismantled the holography studio in 1988.

Galleries and museums: There has been an even more problematic decline in the number of places where the public can see holograms. Where are the retail outlets? Indeed, where are the producers of decorative display holograms to supply them? It's still possible to buy holograms on the web, but we all know that the images seen on a website are not 3D. As well as the MOH in New York, specialist museums or centres in Chicago, Paris, Cologne have all closed. Thankfully the MIT Museum has retained the MOH collection, but has few holograms on display at any given time, other than special exhibitions, such as that mounted for the ISDH at MIT in 2012.

Several major museums still have a collection of holograms, but looking just beyond my own doorstep I see a paradigm for what is happening globally: the V&A has no holograms on display (although it did make its last purchase in 2006 – Paula Dawson's *The Light [for John]*), and the Science Museum dismantled its holography exhibit (mainly examples from *Light Dimensions*) in the noughties. The HoloCenter's Virtual Museum of Holography is an important initiative, but still no substitute for seeing an actual hologram in front of one's eyes.

An exception to this rundown of interest in holograms in the established museums is through the work of the Hellenic Institute of Holography and its *OptoClones*®, excellent holographic recordings of museum pieces, including the Fabergé Eggs of the collection in St Petersburg, Russia.

I don't disparage the efforts of individuals who are still making and/or showing holograms – again, on my own doorstep, Jonathan Ross gets an honourable mention here for his exhibitions at Gallery 286, and Michael Wenyon and Susan Gamble are still making and displaying holograms within their wider explorations of light. Also, many of you attending ISDH '23 are still finding occasional venues for your one-person shows; congratulations and power to you!

Blockbuster exhibitions: When was the last hologram exhibition that was widely reported in the media and had people queuing up to enter? I have nothing more to say on this topic because there is nothing to say.

Meetings: I doff my hat to the ISDH core team for keeping this meeting going; perhaps it helps that it's every three years instead of annually. And SPIE's Practical Holography will chalk up number 38 next year, but attendance – in the low tens – is a fraction of its late 1980s/1990s peak. The smaller meetings have disappeared with the organisations that organised them: the RPS Holography Group, the San Francisco holography group and others. HODIC in Japan continues to carry the flag…

However, in-person meetings have been supplemented and complemented by social media groups; Facebook hosts two holography forums (or, for the pedants reading this, fora) which focus on display holography, one of them with hundreds of members. These are where people can exchange ideas, seek advice, show their work (albeit in 2D or video), buy and sell equipment and generally work as a community.

Material Supply: Silver halide remains the chemistry of choice for most small-scale display hologram producers, but of the companies I mentioned above, only Slavich remains an active producer, thankfully more easily available outside Russia now thanks to Glasnost and an arrangement with Geola in Lithuania (but who knows what the impact of sanctions might be?). French company Ultimate Holography, which developed an excellent emulsion for its own use, now sells it commercially. London company Colour Holographic also made and sold a silver halide emulsion until recently, but on its change of name to TruLife Optics and focus on HOEs for virtual reality, it is no longer selling recording material.

DCG remains the choice of several artists and Slavich now offers a commercial version. DuPont sold its photopolymer business, which has been further sold on so it is now with De La Rue, which makes it only for its own *Izon*® authentication labels, while Dai Nippon similarly does not sell its photopolymer on the open market.

Nomenclature – what is a hologram? I'm adding this topic to those I covered under the previous sub-section on history because it is now an important factor in the lay person's connection with and understanding of holography. Since the mid-noughties I wrote several editorials in *Holography News* railing against the misuse of "hologram" and "holography" as applied to Pepper's Ghost display systems, but eventually I gave up and accepted the inevitable. Language evolves, words take on different meanings, and so the "H" words are now associated with the apparently 3D presentation of projected images that are actual size (e.g. people), full colour, high resolution and moving. These H words also apply to the things that people in this room make, but they are more used to refer to these excellent updates of Pepper's Ghosts.

Summary: Sadly, there has been a decline in the opportunities for display holograms to be made, sold or seen with a concomitant decline in the facilitation of ways and means for those working in display holography to feel part of a community of like-minded people.

In other words: when did you last see a display hologram on sale or display other than one of your own or a colleagues? Or the now occasional – exceptional – use of a display hologram as a corporate PR move?

But let me not be all doom and gloom – there are some bright spots, such as the energy now evident in South Korea, the HoloCenter and the continued success and development of Geola, one of the few companies active in display holography that is still operating after more than 20 years.. I'm sure we'll hear more about Geola's activities from other speakers at ISDH, so I'll only say that they are doing some remarkable work in digital printing of holograms and large format full colour display holograms between their facilities in Lithuania and the UK.

6.3 The Future

This will be the briefest part of my observations on display holography because I am not a soothsayer or fortune teller. In the market reports I referred to above I did forecast future market growth, based on detailed survey data from a significant proportion of hologram producers at the time.[7] Modesty prevents me from referring to the accuracy of my later predictions, but I will say that in 1991 I estimated the market for display holograms at US$3-5m, projecting it growing to $10-20m by 2000. i.e. I gave myself 100% margin for error!

To find similar information today I searched the web for market forecasts on display holography. I found Allied Market Research assessing the market in 2020 at $1.13 bn, projecting it to reach $11.65 bn by 2030. Mordor Intelligence sees market growth at 28% compound annual growth rate (CAGR) to 2028. Market Statsville gives the 2020 market at $2.7 bn, growing to $14.6 bn by 2027.

Guess what? These, and many other market research reports, all refer to the market for 3D imaging display systems – digital, Pepper's Ghosts and so on. That's what I mean about the now-accepted use of the words "hologram" and "holography". *Our* reality is that there is no current measure of the market for display holograms.

So I'm afraid that I am not sanguine about the future for this marvellous medium that we all love. There will continue to be limited training and education opportunities; there will continue to be an enthusiastic cadre of hobbyists and artists working in the medium, and there will be exhibition opportunities for them if they are determined, persuasive and lucky.

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[7] The response rate to the surveys I conducted for those reports was ±70%, exceptionally high for this type of survey. This was due, I believe, to those companies' desire to have this market information, the fact that I asked relevant questions in the survey and I was known.

But all the dreams of the last 50-odd years are evaporating as those non-holographic hologram display techniques usurp true holograms from the market.

7. CONCLUSION

My conclusion is contained in the previous sub-section on the future of display holography. I will add, however, that display holography *is* the only true spatial, 3D, parallax-accurate imaging method yet invented. It's just a shame that to deliver those characteristics requires specialist lighting that dedicated art galleries might achieve but the typical retail environment won't, nor will the advertising and promotional sector (except in those few cases where the holographer has a say in the viewing installation). But in that market accurate colour is also required, to match the Pantone-specified colour for brand logos and fonts. Or, as John Brown puts it: "Holography died for sales/promotion because everybody wanted real colour holography and we just couldn't do it."[7]

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A call to arms: margaret benyon's antiwar holograms

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ABSTRACT

Perhaps best known for her pulsed-laser portraits such as *Tigirl* (1985), Margaret Benyon (1940-2016) was a pioneer of art holography. Trained as a painter, she was one of the first artists to learn holography in 1968. Benyon's practice was highly experimental, combining holography with other artistic mediums and techniques, from sculpture to painting and photography. Her deceptively simple subject matter explored the physical properties of everyday matter—a loaf of bread, a steaming cup of coffee—and the fleeting physicality of the human body. This talk focuses on some of Benyon's lesser-known work: her *Unclear World* series (1979), made at the Royal Military College in Canberra, Australia, and *Pushing Up the Daisies* (1996), which I collectively call her anti-war holograms. Taking an art-historical approach, I read these works alongside other feminist art practices, including Martha Rosler's photomontages, and Benyon's writings in both holography journals and feminist publications. Benyon called for a more politically conscious adoption of holography, reminding artists of their power to shape the ways in which new technologies are used, and whether they help or harm the planet and its people. While Benyon may not have referred to herself as an activist, she used her voice to make an impact in both the international holography community and the greater art world, where she sought to bring wider recognition to the holographic arts. As we consider how to use the new imaging technologies at our disposal, I suggest we pause to revisit Benyon's images and words of caution.

Keywords: Margaret Benyon, art, history, pioneers, UK, Australia

1. INTRODUCTION

THE END OF THE WORLD HAS BEEN NIGH FOR 34 YEARS. In 1979, at the height of the Cold War, the artist Margaret Benyon etched these words into the emulsion of her reflection hologram, *Unclear World II* (Figure 1), which depicts a spiked acid-green cylinder—a scientific model for nuclear fission. It had been thirty-four years since 1945, the dawn of the atomic age. Benyon etched a storybook Planet Earth into the surface of the hologram, complete with cartoon trees, streams, birds, mountains, and a nuclear family, their flatness contrasting the vivid three-dimensional detail of the scientific model, whose spindles threaten to puncture our pretty planet as we know it.

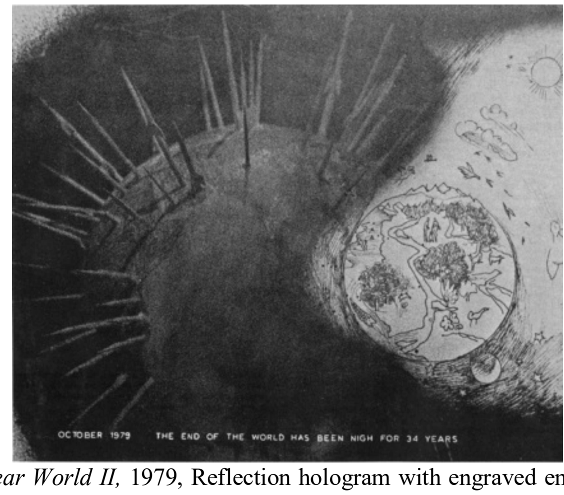

Figure 1. Margaret Benyon, *Unclear World II,* 1979, Reflection hologram with engraved emulsion, 8 x 10 inches (Photograph by Margaret Benyon, reproduced from *Phases: A Twelve-Year Retrospective of the work of Margaret Benyon, Museum of Holography, New York, October 1980–January 1981*)

This was the second mixed-media hologram Benyon made that year entitled *Unclear World*—unclear being an anagram of *nuclear*—the first one (Figure 2) etched with the children's game of snakes and ladders, its rungs bearing the words SALT I, II, and III, referencing the Strategic Arms Limitation Talks—negotiations between the US and Soviet Union that aimed to curtail the manufacture of strategic ballistic missiles.[1]

Figure 2. Margaret Benyon, *Unclear World I,* 1979, Reflection hologram with engraved emulsion (National Gallery of Australia)

It is no coincidence that Benyon produced these works, which she referred to as her "antiwar holograms," at the Australian Royal Military College in Duntroon, Canberra, "with cadets drilling outside" of the laboratory.[2] While these are not the works that Benyon, often called the "mother" of creative holography, is best known for, I want to focus on them today because they illustrate her wider aims for a socially and politically engaged approach to the medium, a position she articulated in her images as well as in her writing. On their own, these "antiwar" holograms might read as heavy-handed or even gimmicky—a word often used by critics to dismiss art holography—but in tandem with her incisive texts, Benyon's message to the international holography community rings loud and clear, even now, seven years since her passing and nearly half a century since she made this work.

2. THE ARTIST'S RESPONSIBILITY

In her seminal article "Holography as an Art Medium," published in the Franco-American journal *Leonardo* in 1973, Benyon addressed "the danger of subcultures of artists proliferating without a broad sense of responsibility."[3] Throughout her career, she continued to warn her readers that the more an art community exists outside the limelight of the mainstream art world, the more likely it will lose sight of this. Even as she witnessed the holography community forming into what she called a "ghetto" at worst and an "embryonic art world" at best, she reminded her peers that "as an artist one is responsible not only to art history but to the society in which one lives."[4]

But what could a modest art holographer, working diligently from their basement in Chicago, Cologne, or Tokyo, offer society at large? Benyon's investment in this question was no doubt rooted in the reception of her early work, which all too often focused on holography's use of the laser and its associations with warfare and weaponry. She had fielded these criticisms since her solo exhibition at Nottingham University Art Gallery in 1969—historically, the first exhibition dedicated to art holography—until as late as 1992, when she wrote, "Art-world criticism of new technology (and holography is increasingly pigeonholed as new technology) seems to be based on [the] suspicion that it is associated with military research."[5] Art historian Sarah Maline has argued that Benyon's early work was precisely "aimed at erasing these connotations."[6] In other words, Benyon pacified the laser by using it to make art. In these early days, her subject matter was not overtly political: she made three-dimensional images of often astonishingly mundane subject matter–a steaming cup of coffee or a loaf of bread growing stale over the course of two weeks (Figure 3).

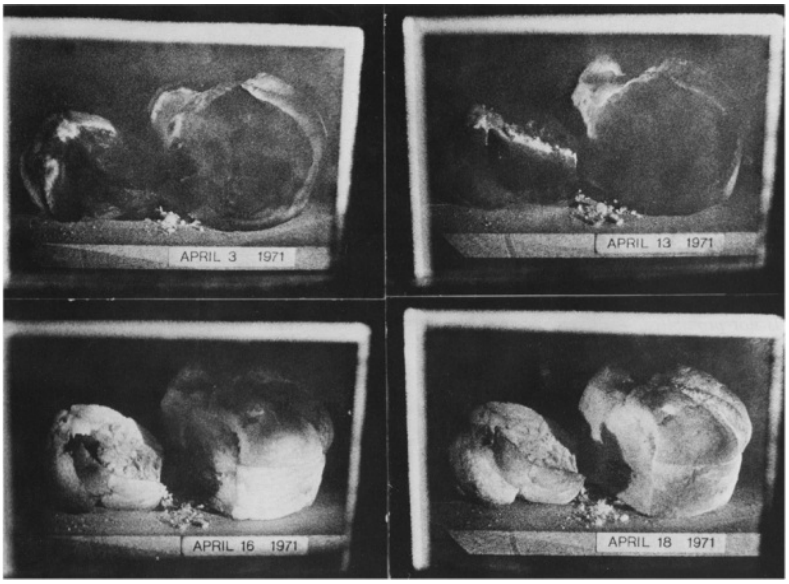

Figure 3. Margaret Benyon, *Bread Series,* 1971, Transmission holograms, four 9 x 12 inch plates, made at Nottingham University (Photograph by Margaret Benyon, reproduced from *Phases: A Twelve-Year Retrospective of the work of Margaret Benyon, Museum of Holography, New York, October 1980–January 1981)*

However, Reading Benyon's images alongside her writing suggests that rather than merely decoupling or dissociating holography from its associations with defense research, she recognized that artists working with emerging technologies had different responsibilities from those working with more traditional media. It is worth quoting her words here at length:

> An artist working with aspects of new technology should share the concern for social misuse of it, instead of sitting back and 'doom-watching.' In working with a medium from the beginning of its development, it should be possible, in a small way, to influence the direction of its use and perhaps even of the direction of further technical research.[7]

For Benyon, the act of using lasers to make art, not war, was a political act. Creative uses of holography had subversive potential: the potential to influence the reception of this technology by a wider public, and the potential to influence its future applications. But it was not until a decade later that she would choose to holograph explicitly political subject matter.

3. A CALL TO ARMS

A photograph of *Unclear World I* was reproduced in the radical feminist journal *Heresies* in 1981, in an issue entitled "*Earthkeeping/Earthshaking: Feminism & Ecology.*" With a violently erupting Mount Saint Helens on the cover (Figure 4)—a geological event that looks not unlike an atomic explosion—the editors asked, "What can women do about the disastrous direction the world is taking?"[8] This time, Benyon's text addresses not only fellow holographers and art-and-technology enthusiasts; here, she speaks to a broader audience, many of whom may have doubted the relevance of holography to radical feminist thought and action. Just as she appropriated a weapon of war for artistic purposes, Benyon appropriated military terminology to call her fellow holographers to arms. She encouraged the use of creative holography as a "countermeasure" to the "sinister" applications of military technologies, and the "infiltration of artists into technological areas not traditionally theirs."[9]

For Benyon, the hologram also provided a metaphor, "a model for integration, for undivided wholeness" within society. Invoking the imagery of a broken hologram, with each piece still showing the whole image, Benyon muses, "there is such a thing as non-fragmentary thinking. It seems a superb model to strive for, in our language, our behavior..."[10] Her words suggest that art need not be fragmented from science and technology, and that holography need not be removed from the idea that art can catalyze social and political change.

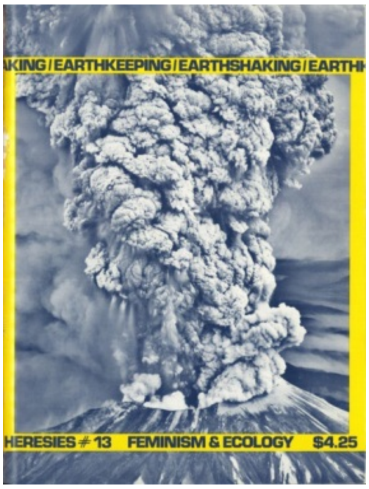

Figure 4. Cover of *Heresies* #13: Earth- keeping/Earthshaking: Feminism & Ecology, 1981

In the 1990s, after moving back to England, Benyon again returned to overtly militaristic themes in her visual art amidst Britain's involvement in the Gulf War. As part of her *Male Cosmetic Series,* she created a pulsed-laser portrait of fellow holographer Jonathan Cope in his Territorial Army uniform (1990).[11] By painting with gouache on the surface of the plate, Benyon added multimedia depth to the work and another layer of camouflage to Cope's likeness. A few years later, she collaged this portrait with her reflection hologram *Wrapped Flowers* (1991) to create a pseudo-double-exposure in which the daisies appear to be growing out of the soldier's helmet.

Figure 5. Margaret Benyon, *Pushing up the daisies,* 1996, Reflection hologram film collage with text, 80.0 x 60.0 cm (National Gallery of Australia)

This composite hologram, entitled *Pushing up the Daisies* (1996, Figure 5), recalls the iconic photographs of anti-war protests in the late 1960s, including Bernie Boston's *Flower Power* and Marc Riboud's *The Ultimate Confrontation: The Flower and the Bayonet*, in which peaceful protestors place flowers in soldiers' gun barrels (Figure 6). In its use of collage to starkly contrast the iconography of war with that of peace, Benyon's work also recalls the American artist Martha Rosler's *House Beautiful* series, which combined photojournalistic images of the Vietnam War—and later, of the wars in Afghanistan and Iraq—with images of domestic spaces cut from interior design magazines (Figure 7). But by using a technology that is so materially linked to war, Benyon's work offers an additional layer of criticality.

Figure 6. (Left) Bernie Boston, *Flower Power,* 1967. Published in *The Washington Evening Star,* October 21, 1967 with the caption "George Harris sticks carnations in gun barrels during an antiwar demonstration at the Pentagon in 1967" (Washington Post Online). (Right) Marc Riboud, *The Ultimate Confrontation: The Flower and the Bayonet,* 1967 Taken October 21, 1967. Published in *Look* magazine December 30, 1969.

Figure 7. Martha Rosler, from *House Beautiful: Bringing the War Home,* 1967-72, Series of twelve cut-and-pasted printed paper on board (Museum of Modern Art, New York).

4. LOOKING BACK, LOOKING FORWARD

While Benyon's antiwar holograms comprise only a small fraction of the work she produced over her extensive and prolific career in creative holography, together with her critical writings, they encapsulate her legacy as someone who cared deeply about the social and political impact of art holography and how the medium was perceived beyond the holography community. Her words and images are particularly resonant in our current moment, when the intersection of art and technology feels, again, deeply contentious.

What Benyon called the "social misuse" of holography was not limited to the Cold War period. Today, holography continues to have certain military applications, including geographic intelligence (which, as Andrew Pepper has argued, can also be useful in disaster and rescue situations), while high-powered lasers continue to be described as "superweapons."[12] Using holography for information storage and security may enact violence on the environment while also threatening the privacy of individuals. Computer-generated holography techniques are already being combined with artificial intelligence research to produce dynamic color holograms on smartphones in real-time, promising to transform human communication.[13] While we have come a long way from the cultural moment of "technophobia" that Benyon faced in the late 1960s, holography continues to be widely misunderstood.[14] For the uninitiated, the word hologram conjures an image of dystopian science fiction, in which dead musicians are resurrected as deepfakes, performing for zombie crowds listening through AirPods and watching through smartphone cameras.

Revisiting Benyon in this moment might serve as a reminder that creative uses of new technologies can shape the reception of those technologies and influence further directions of their use. By creativity, I don't necessarily mean innovation in a business-savvy sense, nor do I mean making art for art's sake. Benyon's holograms did not always *look* anti-war, but even her holograms of the most mundane subject matter worked to pacify the laser by using it to make art, not war. But by making holograms of soldiers and nuclear fission, Benyon forced her viewers, whether they were within or outside of the holography community, to reckon with the notions of violence deeply embedded in the medium and in "high" technology, broadly speaking.

Unfortunately, I never had the opportunity to know Margaret Benyon myself—I first learned holography in 2016, the same year we lost her—so I can only offer my perspective as an art historian and admirer of her work. I can also speak from the standpoint of a newer generation of holographers. I want us to consider how we can continue to carry out Benyon's legacy, extending her project into the twenty-first century. I invite us to brainstorm this question together: As we continue to practice holography, what are we doing to maintain a "sense of responsibility" to our communities, to the history of the medium, and to our planet?

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Holographic structures for interstellar exploration

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ABSTRACT

Journey times and scientific data return are two challenges to Space exploration. Holographic structures that enable novel beam steering methods are being considered for the laser propulsion of ultra-light sail craft as well as for the encoding and the transmission of data. This paper explores ideas developed in conversation with a number of researchers and key innovations that could enable future technologies, along with a series of holograms that are being launched into Space on an Alpha CubeSat.

Current research into photonics structures – including metasurfaces and optical data transmission have extended the applications holographic structures. These understandings and advanced materials are of great interest to the Space exploration community. This paper looks particularly at interstellar exploration and the proposed use of light-sails to travel to the outer regions of our solar system and beyond to nearby star systems.

Keywords: light-sail, nanocraft, metasurface, holography, holographic, interstellar

1. COLLABORATORS

This paper traces the concepts that informed my participation in two collaborative projects. Both projects began in 2016 when I met a catalytic duo - C Bangs, an artist and former NASA Faculty Fellow and Greg Matloff, a light-sail expert and professor at the City University of New York who serves on the advisory board of Breakthrough Starshot.

> The Holographic Messages project also involved Mason Peck, Professor of Aerospace Engineering at Cornell University and the Alpha Cube Sat team of students lead by Joshua Umansky-Castro.
>
> The MicroGRAM: Microwave GRaphene Antenna Metasurface project was also developed with Dr. Joseph E. Meany, who is on the board of the Interstellar Research Group and was at the time of the project working with Savannah River National Laboratory and Les Johnson a physicist, author, and technologist at NASA Marshall Space Flight Center. Additional advice on the project was provided by Darren R. Boyd an electrical engineer specialising antenna design with NASA Marshall Space Flight Center.

My discussions around holographic elements employed in Space science began with Tom Ditto, during 2015 when I was doing a curatorial residency at the Rudie Berkhout Estate in upstate New York. At the time Ditto was developing a holographic method for exoplanet spectroscopy. While I was a collaborator on one of the project's funding submissions, my work took me elsewhere and I was not part of the research team that designed DUET – Dual Use Exoplanet Telescope, described in section 5.3.

2. SENDING MESSAGES INTO SPACE

The act of exploring is also a statement of intent. Journeys to new places make us ask, *who are we, and how do we represent ourselves?* It may seem obvious that Space probes are also messengers into the unknown, but the first messages sent into deep Space were afterthoughts, rapidly created with small budgets by dedicated teams.

2.1 Pioneer & Voyager

Pioneer 10 and 11 were the first two human made objects sent beyond our Solar System. Eric Burgess – a thinker and writer who was a member of the British Interplanetary Society, suggested to Carl Sagan that Pioneer 10 & 11 should carry a message to represent humanity. NASA agreed and the team were given three weeks to deliver the now famous infographic etchings [Fig.1. top left]. Launched in 1972 and 1973, Pioneer 10 will approach Aldebaran after a two million-year journey while Pioneer 11 will get close to Aquila in four million years. The plaques are designed to withstand these journeys.

The Voyager 1 & 2 Golden Records, created in 1977, were also made in a short time and for a long journey. The Voyager probes were launched to take advantage of a once in 176-year planetary alignment allowing them to make close passes of the four outer planets. They were both successful missions sending back information as radio signals to the Deep Space Network – the 70m diameter radio antennas positioned at three locations around Earth. From these missions we learnt about the winds on Jupiter and Saturn and that there are volcanos on Io. The Voyager spacecraft have left the Solar System and will travel through interstellar space for 40,000 years before approaching the next planetary system. The message plaques created a personal connection to these spacecraft as we listened and interpreted the information they sent back to Earth.

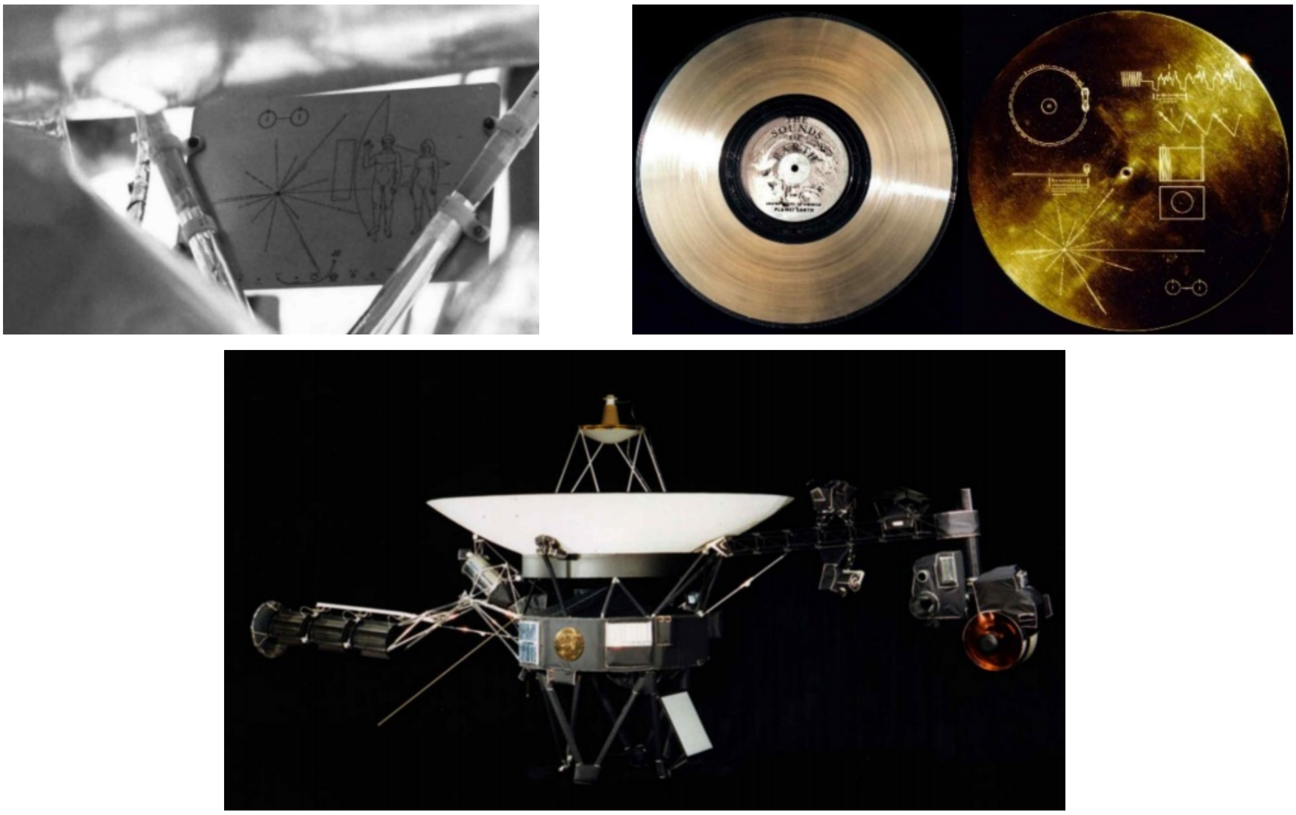


Figure 1. Left, message plaque attached to Pioneer 10; Right, Voyager Golden Record, with attachment to spacecraft shown below.

Encoded and etched onto Voyager's 12″ gold-plated copper disk are 115 images and 90 mins of music with sounds from Earth and voices speaking traditional greetings in 55 languages. On the flip-side is a diagram explaining how to play the record. Gold was used due to its atomic stability. Considering how other beings could sense is an aspect of designing deep Space messages, as well as their longevity.

"The spacecraft will be encountered and the record played only if there are advanced spacefaring civilizations in interstellar space. But the launching of this bottle into the cosmic ocean says something very hopeful about life on this planet." Carl Sagan [https://voyager.jpl.nasa.gov/golden-record/]

A more immediate aspect of these projects is to ask how we represent ourselves as inhabitants of Earth. Sending a message is an opportunity to collaborate and build our identity as a species.

2.2 Holographic Messages Project

Collaboration across disciplines often drives innovation. At the 3rd International Academy of Astronautics Symposium on Realistic Near-Term Advanced Scientific Space Missions in 2000, Dr Robert Forward the American physicist and science fiction writer, suggested to artist C Bangs that she explore holography as a medium for interstellar message plaques.

C Bangs reached out the Center for the Holographic Arts – HoloCenter and produced a prototype holographic message plaque at the HoloCenter's Court Square studio in Long Island City, New York during 2001. The artwork used a multiplex technique to combine six images that were then layered with the Apollo 16 photograph of Earth. The hologram was made from four two-dimensional drawings – the equations for solar-sail acceleration, a diagram of an interstellar probe trajectory, Earths location in the solar system and a line drawing of two humans in the spirit of Pioneer 10/11. There were also two 3D holograms of a sculptured man and of a woman.

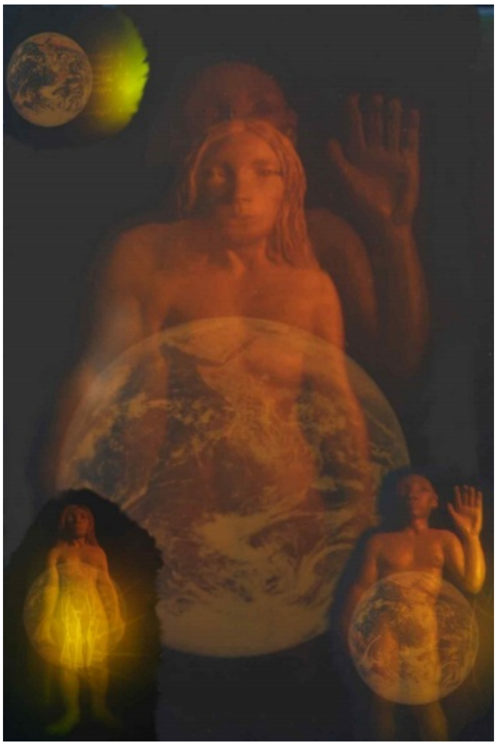


Figure 2. Holographic Message Plaque created by C Bangs, 2001

This artwork resulted in a hologram installation at NASA and contributed to the paper 'The Interstellar Probe (ISP): Pre-perihelion trajectories and application of holography' [Matloff 2002].

In 2016 I met with C Bangs and Greg Matloff to discuss a new generation of holographic message plaques for light-sails, including tiny laser propelled nanocraft. Our conversions developed into a number of proposals and projects. Designs were developed by looking at mission requirements and available hologram recording methods.

My work with holograms has often involved multiplexing so I began considering what sort of imaging this could enable for a message from Earth. Holographic multiplexing could enable hundreds or even thousands of people to contribute images, or be employed to record animations, visual dynamics and/or digitally compiled volumetric images. Designing universal images raised questions about our assumptions of representation. *What can be expressed without assuming two horizontally spaced single aperture eyes and sight in the visual spectrum?* Potentially more universal messages would be broad spectrum patterned designs of harmonic beauty.

2.3 Alpha CubeSat

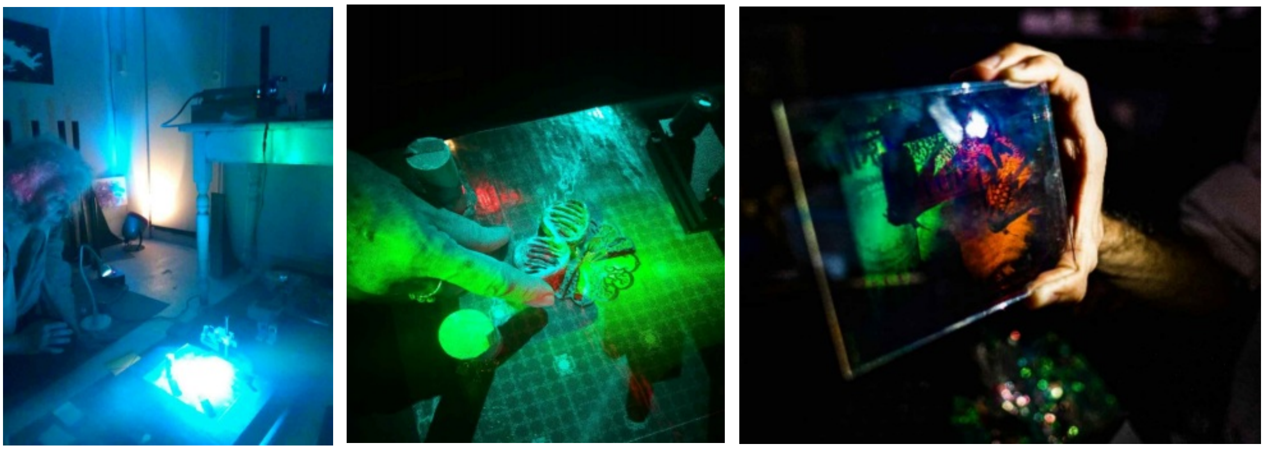
CubeSats are 10 x 10 x 10 cm research spacecraft often made from off the shelf electronics. Some satellites are a single CubeSat unit while others combine multiple units. The Alpha CubeSat team at Cornell Space Systems Design Studio developed a novel unfolding deployment method where a 0.18 mm thick light-sail is spring loaded within a CubeSat.

While our research was looking at holographic structures for the sail material it was not possible within the project time or budget to emboss or fabricate the sail with holograms. Instead we created holograms for the solar panels on the CubeSat, using the project to highlight the possibilities for holograms to carry messages and have mission capabilities.

The series of holograms for the CubeSat were recorded from sculptures, painted tiles and retro-reflective elements created by artist C Bangs. Her imagery is inspired by nature, with entwined details to capture the complexity of life. The imagery has the aesthetic of a seed with enfolded complexity.

To experiment with how holographic elements could enable unique visual signatures of reflected light, each hologram was multiplexed with three reflection images – one in red, one in green and one in blue. Each recording/replay angle was spaced at 120-degrees around the plate and at an inclination of ~ 45-degrees to the normal. The holograms were recorded on 4x5″ Liti- C-RT20 photopolymer film that was then cut down to 10 x 10 cm for lamination onto the sides of the CubeSat.

One challenge was to work out how to exposure the hologram with the variation of the photopolymer's wavelength sensitivity and with the different powers of available lasers – a 20 mW HeNe for red, a 100 mW diode for green and a 40 mW diode for blue. After some experimenting the exposure pattern that worked the best was to start the red exposure, then the blue, then green, stop the green when the plate was nearly completely exposed, followed by the blue and then the red. The resulting holograms could then be rotated with the blue, green and red images replaying one after the other. Due to the change in reconstruction angle the imagery appears to morph and swing. The compromise of this approach is



that no single illumination angle was as bright as when recorded with only a single reference angle.

Figure 3. Recording the holograms with C Bangs in my basement in New York; setting up for the 'DNA' recording; and 'Moth' one of the eight holograms created.

Out of the eight holograms made four are being chosen, including selection by the public during the exhibition *POSTCARDS FROM EARTH: HOLOGRAMS ON AN INTERSTELLAR JOURNEY* at the Intrepid Sea, Air & Space Museum in New York. The chosen holograms will be laminated to the Alpha Cube Sat solar panels and launched from the International Space Station as part of NASA's CubeSat Launch Initiative.

Fig 4. *POSTCARDS FROM EARTH: HOLOGRAMS ON AN INTERSTELLAR JOURNEY*, Intrepid Sea, Air & Space Museum. New York since February 16, 2023, photos by C Bangs.

2.4 Breakthrough Initiatives

The Breakthrough Initiatives support open access research on fundamental questions of our universe, "*Are we alone? Are there habitable worlds in our galactic neighbourhood? Can we make the great leap to the stars? And can we think and act together – as one world in the cosmos?*" [https://breakthroughinitiatives.org/]. The Breakthrough Starshot initiative seeks to send a probe to the nearest star-system Alpha Centauri. The proposed spacecraft to reach Alpha Centauri within 20 years is a 'Nanocraft' with a gram-scale sensing and communication functions and a light-sail propelled by laser.

The challenges for such an endeavour are huge, but these challenges inspire science and collaboration. The miniaturisation of consumer electronics has driven much of this research, such as ultra-thin (~25nm thick) holograms – created by using topological insulators that produced a low refractive index surface and ultra-high refractive index bulk to enable the ultra-thin patterning to act like resonant cavities [Yue 2017].

Photonic structures could offer novel solutions to the creation of light-sails that can withstand the gigawatt power of a laser and be stable within its beam during a 10 minutes acceleration. At the April 2018 Breakthrough Advisory board meeting in Palo Alto, Matloff, Bangs and I proposed the use of holographic beam steering to control the reflection geometry of the light-sail for stable beam riding. To demonstrate holographic beam steering I created small holograms of a concave mirrored surface that were then passed around with a flashlight and flipped between normal reconstruction and pseudoscopic replay as virtual convex surface.

Thinking geometrical, one solution would be to create a reflective sphere and establish a Bernoulli like system, where the laminar flow can suspend the sphere within the beam. A laser array with rings of intensity is another approach while scanning the beam foci- similar to how optical tweezers move particles, is another method for position control.

Surface patterning to achieve holographic beam steering offers further control such as torque forces that could stabilise the craft, produce spin and/or maintain a sail shape. Further study into how holographic structures distribute photonic pressure is required as well as the development of light-sail materials.

The laser propulsion of interstellar probes leads to further possibilities for embedding information within the sail. Using laser illumination holograms are able to reconstruct deep 3D images or can be multiplexed and then scanned to reveal pages of information, sequences of images, movies or animated scenes. In general, reflection holograms reconstruct a selected range of wavelengths while transmission holograms diffract the source illumination spectrum.

3. LIGHT SAILING

3.1 Solar Sailing

Harnessing the photonic pressure of the sun, solar sailing enables spacecraft to be continuously accelerated. To achieve fast velocities sail-craft require highly reflective sails with a tiny mass per unit area. Most solar-sails are made from ultra-thin 4~5nm metallic foils on Polymide films – such as Kapton. To achieve sail flatness inflatable booms, and booms that unroll like a tape measure have been used, while spinning the craft can also enable flattening. Controlling pressure vectors with holographic elements across the surface could also establish sail spin, or provide flattening

IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) created by the Japan Aerospace Exploration Agency was the first spacecraft to successfully fly using a solar-sail. Launched in 2010 the mission to Venus included a number of novel designs. Altitude control was achieved by 80 liquid crystal panels that could change the reflective properties of the sail, while thin-film solar panels harvested energy.

To engage the public with the solar-sail mission a campaign was launched by Japan Aerospace Exploration Agency and The Planetary Society to collect words of encouragement from all over the world.

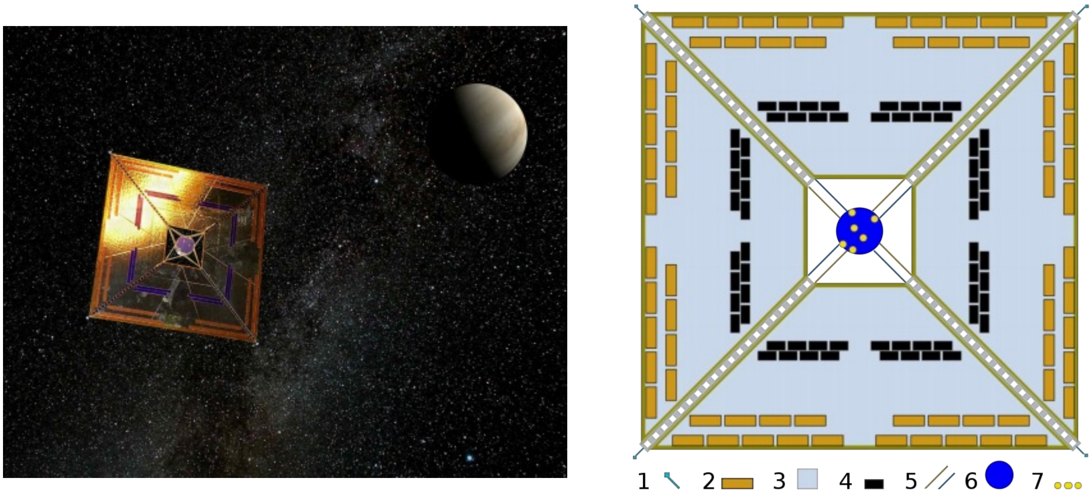


Figure 5. a) IKAROS space-probe with solar-sail in flight (artist's depiction) showing a typical square sail configuration by Andrzej Mirecki. b) IKAROS sail schematic diagram: (blue square on a line) Tip mass 0.5 kg (1.1 lb), 1 of 4. (orange rectangle) Liquid crystal device, 1 of 80. (blue square) Membrane 7.5 µm (0.00030 in) thick, 20 m (66 ft) on the diagonal. (black rectangle) Solar cells 25 µm (0.00098 in) thick. (yellow and blue lines) Tethers. (blue disc) Main body. (yellow dots) Instruments.

While the continuous stream of the solar photon breeze offers a propulsion method to explore the solar system and accelerate probes into interstellar space, solar-sails are also being designed to maintaining satellite positions, such as a Low Earth Orbits or the artificial orbit between the Earth and Sun – as was planned for the Solar Cruiser mission. Holographic elements have been proposed as a method to maintain orbital stability by including a holographic solar photon thruster [Matloff 2002].

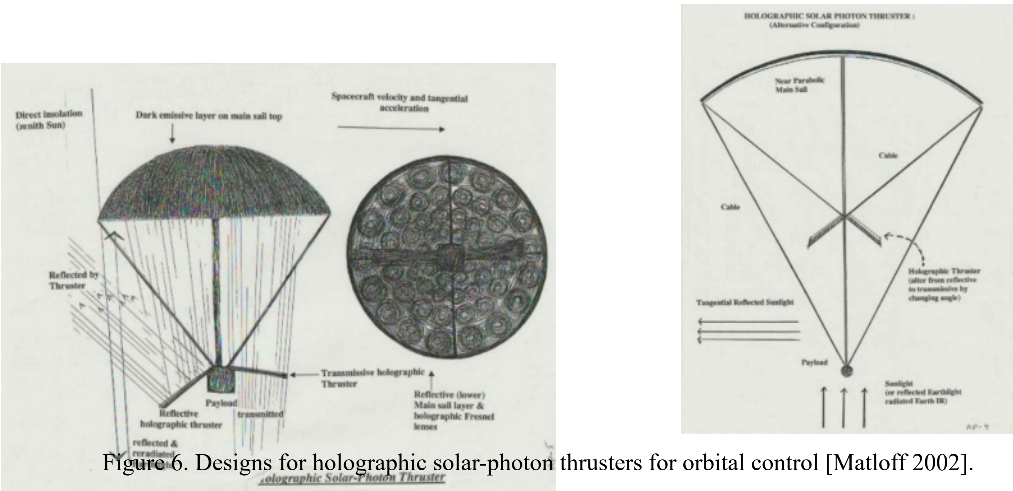


Figure 6. Designs for holographic solar-photon thrusters for orbital control [Matloff 2002].

Space mission are difficult, expensive and unforgiving. To date only half the missions to Mars have been successful. NASA's proposed Solar Cruiser mission for a solar-sail with and area of 1,672 m^2 – the area of around six tennis courts was put on hold in 2022. Meanwhile NASA is working on the much smaller Advanced Composite Solar Sail System (ACS3) for Earth orbit which will test light-weight carbon fiber boom deployment. These booms will unwrap from a central spindle as developed for the 86 m^2 aluminized polyimide 2.5 µm thick sail of the Near-Earth Asteroid Scout mission. The Near-Earth Asteroid Scout was launched in 2022 but could not be contacted.

As well as the large space agencies The Planetary Society have launched solar-sails. LightSail 2 was a crowd funded mission accompanied by a disc with the names of everyone who contributed.

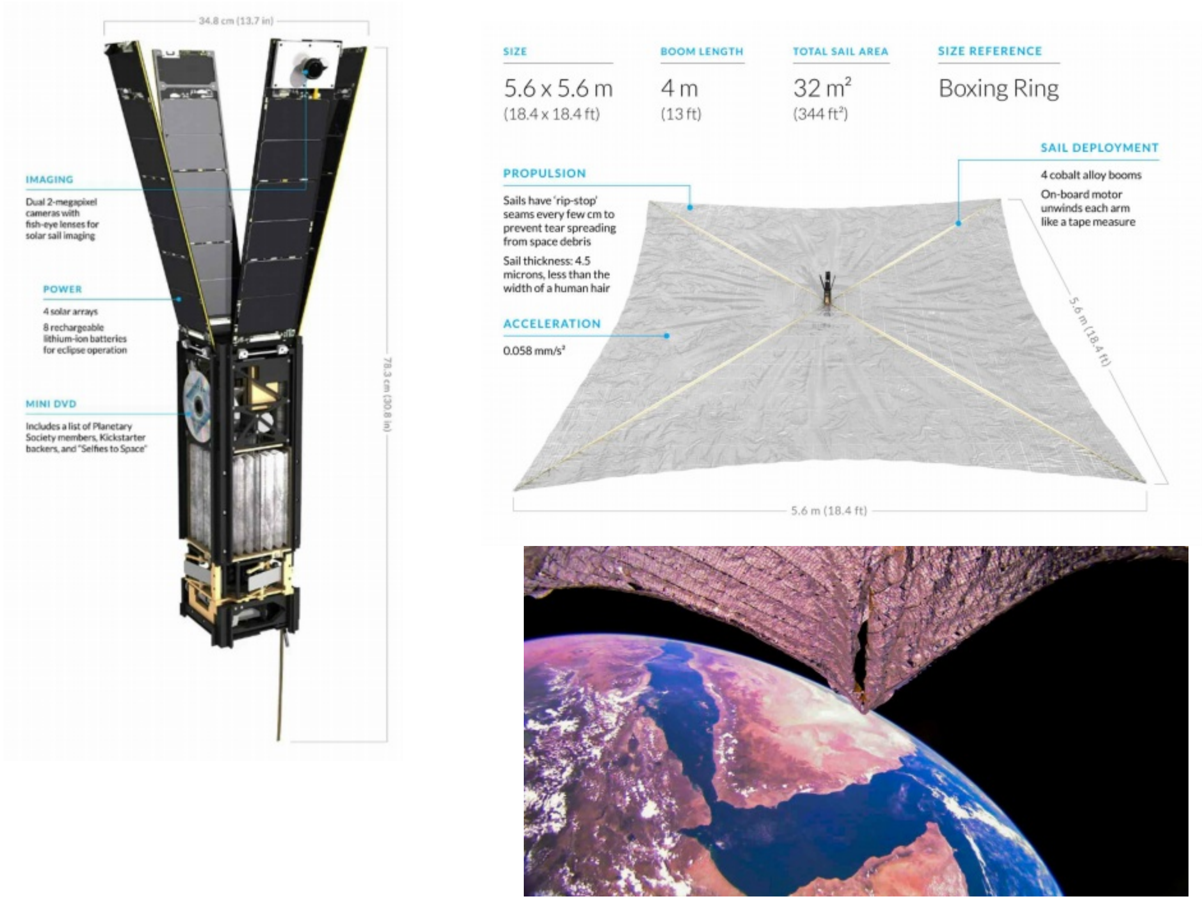


Figure 7. The Planetary Society, LightSail 2 with photo taken by the spacecraft on Oct. 14, 2022 of Gulf of Aden and Red Sea, bottom right, this image has been color-adjusted and some distortion from the camera's 180-degree fisheye lens has been removed.

Building on the success of IKAROS the Japan Aerospace Exploration Agency proposed OKEANOS – a mission to explore the Trojan asteroids that share Jupiter's orbit around the Sun. The design developed used hybrid solar-sail propulsion, where energy is also harvested from the 1600 m^2 sail to power an electric ion engine. At the time of writing this mission has not been funded. Matloff [2002] proposed using an electrically conducting sail to function as a magnometer, able to both take measurements and produce current. Design thinking then addresses how a laced electrically conducting structure could harness power while adding strength that maintains the sail shape and prevents rips.

3.2 Perforation and diffraction

Matloff's calculations to enable interstellar solar sailing probes requires the spacecraft to be launched towards the sun - a pre-perihelion trajectory, where it can gain the most photonic force. These trajectories offer greater acceleration but require materials to withstand extreme solar radiation.

Metallic reflection has limits and is vulnerable to re-radiation issues. In 1983 Freeman Dyson suggested perforating the sail to reduce the weight density and mitigate heat stress. With a close pass of the sun, another method of mass reduction is to burn-off structural layers and components that were required for unfurling and positioning but are unnecessary once the sail is deployed.

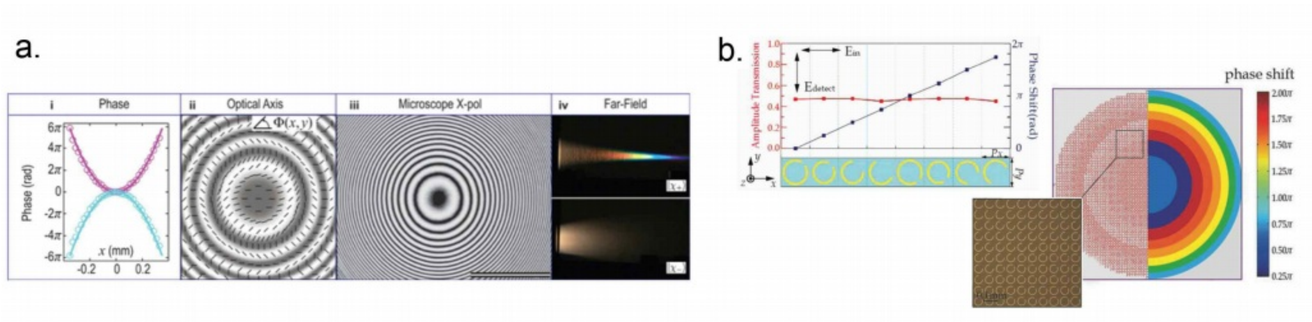
With negligible absorption, diffractive sails offer an alternative as they do not have the heat stress and re-radiation issues of metallic reflection. Interestingly, as the photonic pressure of diffraction does not require the photons to be transmitted, the photons could be further used for energy harvesting [Swartzlander, 2018]. Fabrication of nanogrid or reflective wire sails can could be achieved with optical lithography or UV holography, such as the fabrication of doped carbon nano-tubes as proposed by Speith and Zubrin [1999].

By integrating diffractive elements into solar-sails novel possibilities emerge.

4 METAMATERIALS

Metamaterials are subwavelength structures can manipulate light with multiple degrees of freedom. The subwavelength patterning of metasurfaces enable the miniaturisation and tunability of electro-magnetic processes.

Replacing a converging lens with a metasurfaces reduces the material required and the cost of fabrication. A simple converging lens metasurfaces however produces large phase dispersion with the focal length dependent on frequency (chromatic aberration). This can be addressed with more complex patterning [Wang, S. 2017], or could be utilised for signal multiplexing. Reflective arrays and metasurface lenses with negative ‘refraction’ - where the focal point is on the



same side as the beam, are more frequency selective and can therefore be designed as signal filters.

Figure 8. a) Interference geometric phase hologram lens created with direct writing using of patterns as an inhomogeneous optical axis profile in thin films with a few μm thickness [Jihwan Kim 2015]. b) Variation of unit cell pattern to create a Terahertz/sub millimeter focusing element with a C shaped split ring resonator [Wang, Q. 2015].

The resonant unit cell array of metasurfaces, that enables control of the EM profile, can also be connected to circuits to detect and transmit waves. Further applications of metasurfaces include electrically tunable beam steering as well as antenna transmitters and detectors. A metamaterial can be designed as a tunable artificial impedance surface to enabled directional control, even if the surface is not flat or the signal changes orientation. Metasurfaces designed for energy harvesting have mission enhancing potential and are generating research interest. The vision is that deployable metasurfaces will be embedded with multiple EM functions in the Space environment.

Ring resonators and other periodic patterns have driven metasurfaces research, in part due to design simplicity and ability to fabricate. However computational analysis that also considers supra-wavelength features, has shown that by varying the unit cell structure further topology optimisation of a metasurface lens can be achieved [Fig. 9, Lin, 2017].

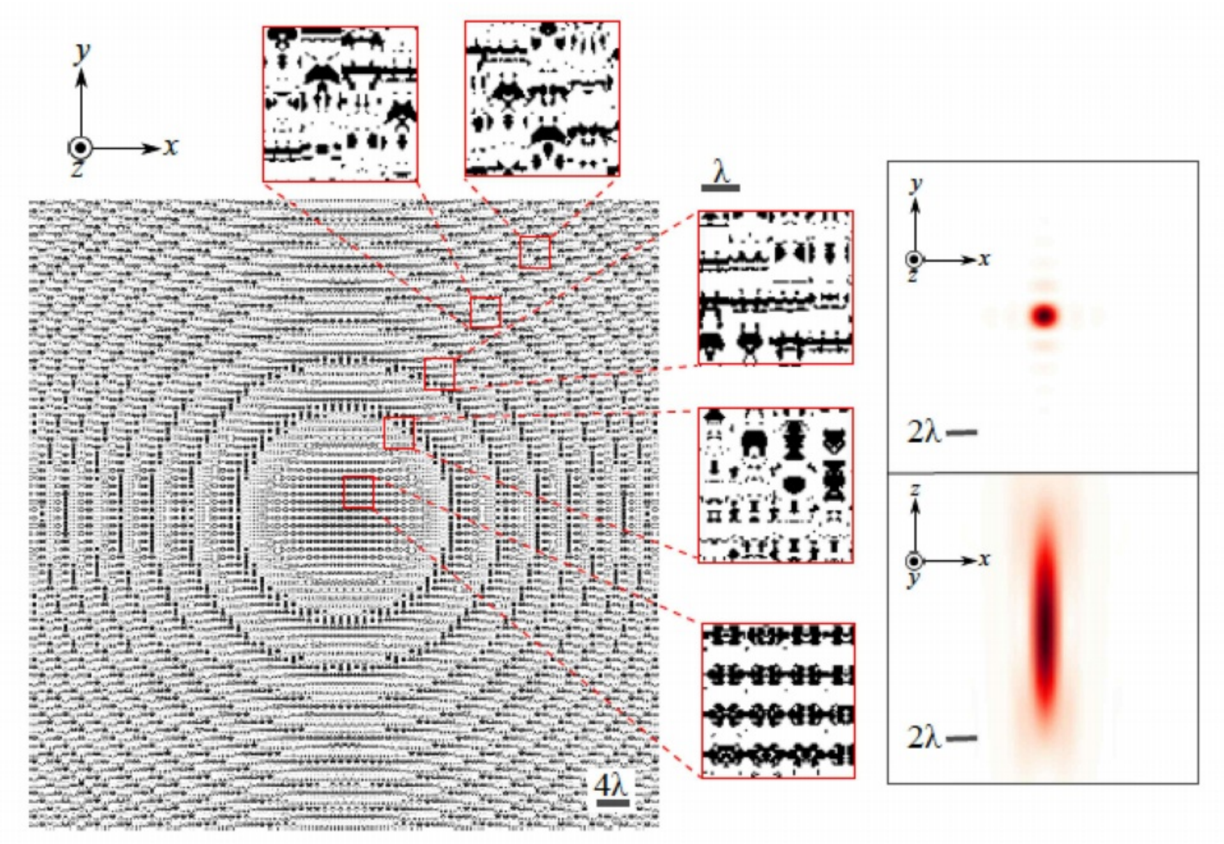


Figure 9. A group at MIT optimised the patterning of a metalens using an extensive library of shapes. The lens consists of a single TiO2 layer above the silica substrate. The far field profile is obtained by locally periodic approximation, showing diffraction-limited focusing. [Lin, 2017].

Metasurfaces based on holography enable more flexibility and control of polarization, beam steering, and spectral dispersion. The surface patterning of holographic antenna can be tuned to a frequency of interest or designed to scan frequencies [Liu, 2016].

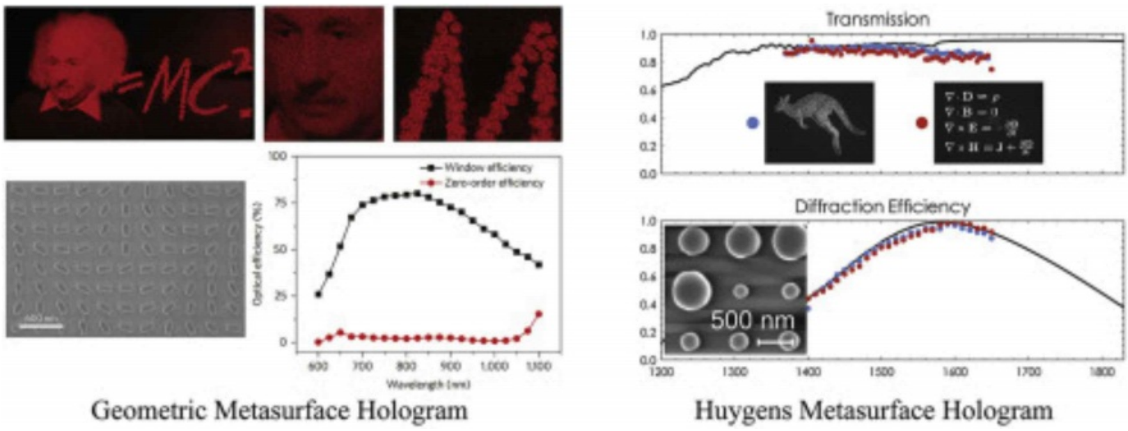


Figure 10. Examples of metasurface holograms. *Metasurface optical holography* [Deng, 2017].

Designing the next generation of light-sails requires consideration of their ability to carry and communicate information and to harvest, store and distribute energy. The fabrication of micro-to-nano scale structures that enable the control of light, energy and information is becoming more feasible. Applications that combine the harvesting and storing energy are particularly exciting. Photonic structures are also important in more efficiently dealing with the burgeoning creation, transmission, processing and storage of information.

5. SPACE COMMUNICATIONS

The capability to unfurl large-area solar-sails in the Space environment also enables a new generation of communication and sensing instruments. With the distances involved in Space communications control of the radiation pattern and directivity over a large aperture are key to antenna architecture. The engineering challenges of positioning and surface flatness remain, with different tolerances for each application.

5.1 MarCO – Mars Cube One

MarCO A & B were two CubeSats that accompanied NASA's InSight lander to Mars in 2018. They were the first CubeSats to be used beyond Earth and served as communication relays between the lander and Earth as well as carrying their own experiments as they flew by Mars. Each of the MarCOs was equipped with a high-gain X-band antenna that sent data at 8 kbps back to Earth. The surface patterning of these flat-panel metasurface reflector arrays shaped the X-band microwave beam as if it was a bounced off a reflective parabolic dish.

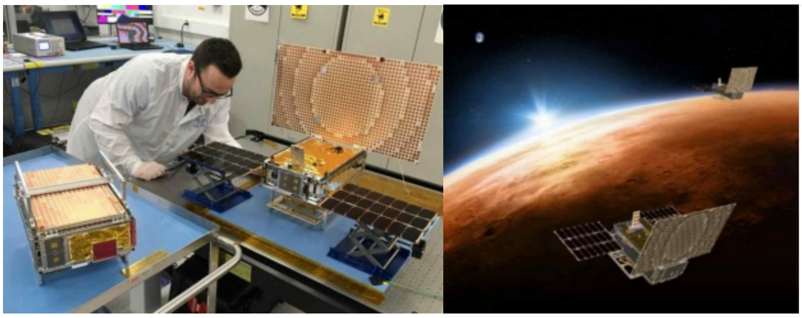


Figure 11. a) JPL engineer Joel Steinkraus works with one of the MarCO CubeSats during an outdoor test of its solar arrays. b) Artist image of MarCO mission. c) MarCO -B, image while flying away from Mars after InSight landed, 26 November 2018, [NASA/JPL-Caltech, https://www.jpl.nasa.gov/missions/mars-cube-one-marco]

5.2 MicroGRAM project

The MicroGRAM project was a NASA Innovative Advanced Concepts award proposal to design a new type of ultralightweight, large-area Microwave GRaphene Antenna Metasurface to replace parabolic reflector communication dishes aboard deep Space science missions. Our proposal was to laser induced graphene structures to direct-write metasurface holograms. These sub-wavelength periodic variations would be optimised to create geometric phase shifts and resonant phase delays for beam steering. Laser induced graphene creates a porous foam that is flexible and can be printed onto polyimide sail substrates. This is a cost-effective method for the rapid prototyping of structures that can shape Microwave frequencies (1 m to 1 mm wavelengths). Microwave communications have many applications and enable signals from Space to penetrate the atmosphere and reach ground-based radio telescopes.

In addition to offering a low-mass replacement for traditional antenna functions, these metasurfaces could be designed to function off axis or with multiple focal points for signal multiplexing and/or signal filtering.

Research into microwave- scale graphene metasurfaces would also enable the testing of novel surfaces patterning for beam riding light-sails and other applications. These laser-printable patterns would enable a wide range of experimentation before the more complex fabrication of nanometric structures for laser accelerated sail-craft

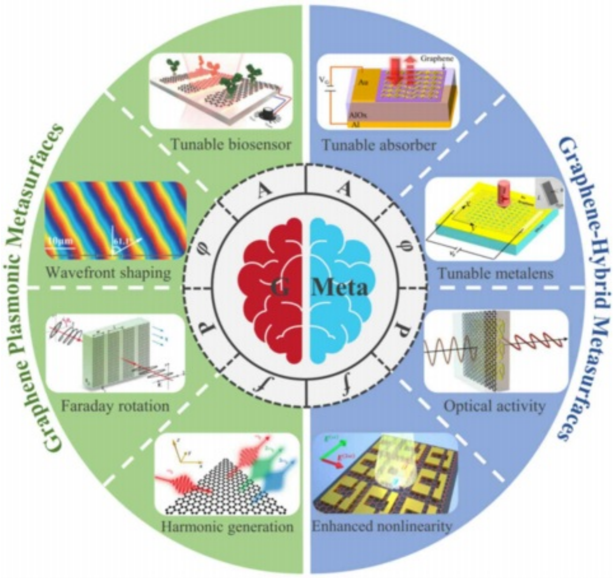


Figure 12. Overview of state-of-the-art selected functionalities of dynamic metasurfaces and metadevices empowered by graphene, OEA [Zeng 2022]

5.3 Holographic space telescopes

Using a large-area diffraction grating as the primary objective Tom Ditto proposed a new type of large Space telescope for investigating planets around other suns. These telescopes use a Holographic Optical Element as the primary objective. Through a series of NASA Innovative Advanced Concepts awards he expanded this concept into a range of configurations including methods to capture single wavelengths of multiple stars or all the wavelengths of light coming from a single star. The Dual Use Exoplanet Telescope (DUET) design creates a circular spectrogram of the light from a star [Ditto, 2020]. Using angular differential imaging this large Space telescope could observe the reflected light of exoplanets – optical signatures from which we can learn about these planets.

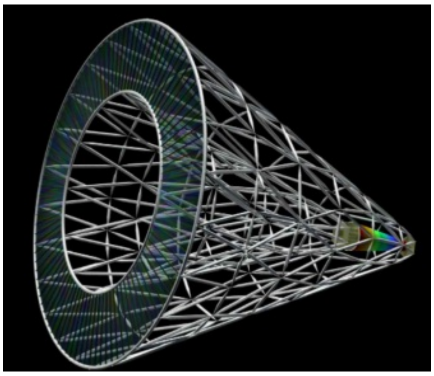
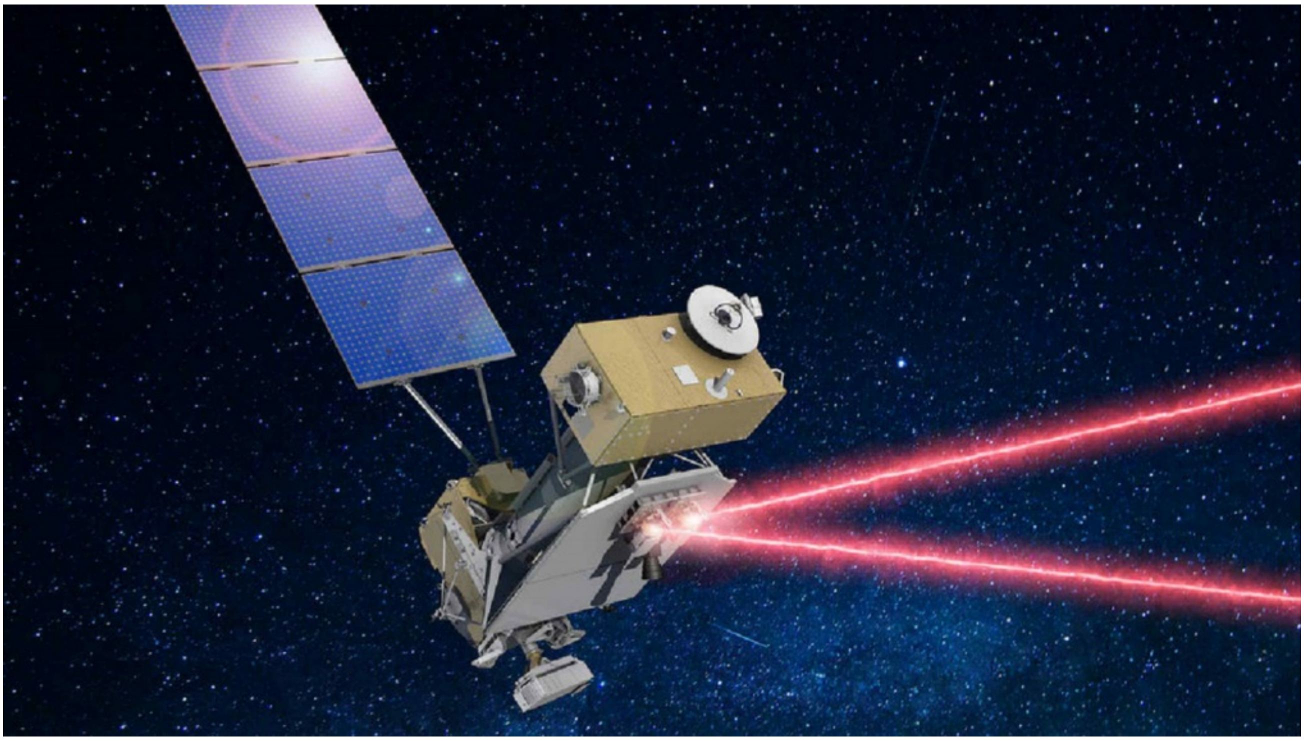


Figure 13. Dual Use Exoplanet Telescope proposed large area deployable diffraction grating exoplanet telescope [Ditto, 2020]

5.4 Wavelengths and structures

Radio astronomy and communication has dominated deep Space exploration because these signals can penetrate Earth's atmosphere even with cloud cover. Optical communication however offers much faster rates of data transmission with the ability to encode information using the angular momentum offering theoretically unbound information channels and encryption [Hui Yang, 2023].

With more and more satellites in orbit, and the deployment of communication relay spacecraft, optical wavelengths and structures become more advantageous. NASA is currently developing infra-red satellite relays with weather dependent



ground connection to Hawaii.

Figure 14. An artist's rendering of the Laser Communications Relay Demonstration on the Space Test Program Satellite (STPSat-6). [NASA, https://www.nasa.gov/mission_pages/tdm/lcrd/index.html]

6. REDUNDANCY AND SELF-REPAIR

Space probes, are subject to micro meteors that can puncture holes in thin materials. With a simple reflective sail, the main issue is to prevent these tiny perforations causing rips. With more complex sails that include sensing, communication or energy harvesting elements, designs need to consider redundancy and operational performance over extended journey times.

One of the appeals of holographic data storage is the separation of information from the physical/digital structure – the fundamental aspect of a hologram being a perspective window of the data set, so that damage to the recording structure does not cause data loss. Damage however can degrade the information quality, that can then be restored through routine processes. *Could similar architecture be applied to spacecraft surfaces? Would such repairs require active materials, or could the metasurface have adaptive electromagnetic properties to compensate for physical damage?*

This adaptability may also be the key to addressing beam steering corrections and wrinkles from unfurling errors.

For Breakthrough Starshot redundancy can be addressed by the mass production of Nanocraft that are then launched as a swarm. Such a swarm of sensors also sets up the conditions for light field imaging with the distributed imaging points creating a holographic data set.

7. VIRTUAL SPACE

The ability to rearrange perspective and reshape visual space is one of the reasons I am fascinated by holographic art. With my own hologram artwork, perspective becomes a dynamic quality. The installations I have made with holograms encourage exploration and an awareness that is beyond ourselves, and yet each holographic image is animated by the viewer.

A hologram can be a window into other spaces, and ‘holographic’ has become synonymous with realistic virtual experiences or any form of illusion– whether or not holograms are involved. Images captured by probes and telescopes are how most of us explore Space. Currently there is an explosion in the design of virtual and mixed reality so our ability to ‘visit’ Space is taking on new forms. Artists are also creating experiences that are no longer anchored to the physicality of being on Earth.

For the humans who do inhabit the ISS and future space bases, interiors with holographic art can expand visual space, enable dynamic light and bring the aesthetics of nature into small artificial environments. Artists including Setsuko Ishii and Betsy Connors have made stunning hologram art installations that bring nature inside.

8. DESIGNS FOR EXPLORATION

Through a series of discussions with Greg Matloff, C Bangs, Les Johnson and Joseph Meany in 2019 and 2020 numerous ideas evolved by bringing light-sail mission requirements together with advances in holographic structures, metasurfaces and laser induced graphene.

Working in the Space environment brings an interesting set of material science challenges. Materials need to be able to withstand intense temperature fluctuations. While solar radiation can produce extreme heat, instruments intended for deep Space also need to be able to operate at near zero-degrees Kelvin.

Every gram counts when acceleration is extrapolated to journey times over huge distances. To enable an interstellar journey, and data return within human lifetime, we will need to develop nanometric sail-structures with integrated sensors and we also propose a holographic message. The process of designing this message will enable the public to engage with the mission and Space science. There is a personal touch to a message carrying spacecraft, connecting us with its journey. As if we are reaching out.

The holographic diffraction of light enables even a tiny probe to have a distinctive visual appearance. This diffraction could also be designed make the probe detectable through a broad spectrum and highlight that it is an ambassador of an advanced, peaceful civilization. The beauty of design is important. The messages that we send into Space are also messages for future generations on Earth. They speak of a unified approach, to not only get through the turmoil of current crises but a shared goal to thrive as a species.

The Breakthrough Starshot project brings together innovation and imagination. Collaboration and shared research are producing new engineering solutions to extend our reach off planet and knowledge of the galaxy. The questions asked are as important as the solutions found. This dialogue around why and how to engage with our galaxial neighbours makes us look deeply at life and consciousness.

Going to Space is not an option out of Earths problems but helps us re-think global issues and consider sustainable justice in a confined system. Recycling takes on a whole new meaning on a Space station or off planet base. Humans have launched so much stuff off planet that there are already issues with the debris in orbit. The era of cleaning-up Earth has slowly begun with it a growing adoption of design that considers humanities long future.

Endeavors such as Space exploration require a collaborative envisioning of how we want to move forward as a species. The design process brings together people and ideas with a spirit of sharing and in the process, we get beyond *‘is it possible’* to consider a range of possibilities and diverse implications. Holographic design is a confluence of physics and imagination, so is Space exploration. While enabled by technology, innovation is driven by curiosity and vision.

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Efficient production of holograms for hands-on holography course

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ABSTRACT

The University of Toronto offers a hands-on holography course, where students produce display holograms with artistic content. With an enrolment around 30 students, who work in teams of two, we need to produce reliably around 15 holograms before each project deadline, while giving students freedom and flexibility to use their creativity. Here we describe the technical innovations which ensure that most students produce successful holograms quickly. The student's first project uses real-world objects. A second project is printed from digital 3D graphics models into a white-light viewable, full-colour transmission hologram. Both are master-transfer holograms, measuring 20x30 cm. The full-colour holograms are produced as three rainbow holograms recorded simultaneously into the transfer. To reconstruct the three master rainbow holograms, we use three collimated laser beams that meet in a cylindrical lens and are expanded together. This allows us to rapidly balance the intensities of the three colors using variable attenuators. To adjust the intensity ratio between object and reference beams, we use two remote-controlled shutters and two wireless power meters connected via Bluetooth (BLE) to an Android Tablet that is mounted above the optical table. This allows us to measure simultaneously both the object and reference beam intensities, while adjusting them with a half-wave-plate. Using this equipment, novice laser lab users, working under the supervision of a teaching assistant, record successful holograms on their first try. Most of them rate the learning experience in the holography studio very highly.

Keywords: Undergraduate course, reliability, novice users, master-transfer process, wireless power meter, digital hologram

1. INTRODUCTION

The University of Toronto offers a holography[1] course as a breadth option[2], for students from a wide range of programs of study in the Faculty of Arts and Science. Its main purpose is to use the medium of holography to teach concepts of both optical science and of holographic art. Students must complete two projects in this course by working hands-on in a laboratory to produce holograms. For the vast majority of students, this is the first time when they use lasers or any of the other equipment necessary for the production of holograms. Artistic holography is normally a slow process, where the artist is usually recording multiple holograms in order to select and fine-tune visual aspects such as brightness, shadows, focal point, etc., to precisely convey the intended message. Our students, however, do not have the luxury of making multiple attempts at recording a hologram, selecting the one that is most successful. This is because we only have one laser and optical table, and all students in the class need to be given time before the project deadline. Therefore, students normally get only one attempt at making their hologram.

With the advanced equipment and chemical processing steps[3] necessary for making holograms, avoiding common pitfalls and mistakes becomes very important, to ensure that every student produces a good hologram. Therefore, we have optimized our equipment to make the production of holograms as efficient as possible for our students. With the limited amount of time in the laboratory, we want to help students spend as much time as possible on the content and material to be recorded, instead of making the many fine adjustments that people with expertise in the laser lab are used to making routinely.

When the recording of holograms is more efficient, we make holography accessible to a wider range of students, by being able to increase the class size. We also avoid having to require prior knowledge in optics, which would make the course inaccessible to the majority of students at our university. In designing setups that are relatively easy for students to implement, we have to make sure that they do not impede their creativity. The main challenge is to find the right balance between guiding the students "too much" towards a standard setup vs. not guiding them enough, in which case they must discover and debug the best setups by themselves.

There are approximately 30 students in the class who form around 15 teams. We therefore need to be able to record 15 holograms of reasonable quality before each project deadline. Usually, each team gets about 1.5 hours of studio time to complete the master hologram, and 1.5 hours for the transfer.

2. HOLOGRAMS AND EQUIPMENT

All holograms in this course are 20 x 30 cm in size. For the first project, students produce a real-world-object hologram[4,5]. This can be either a reflection hologram, which produces a green image, or a rainbow transmission[6] hologram. The second project is a digital hologram (also called holographic stereogram), recorded as a pseudo-colour white light transmission hologram, which reproduces the red, green and blue colours through three overlapping rainbow holograms. We provide the necessary mounts to display these kinds of holograms.

The holograms are recorded on Geola VRP-M film. Transmission holograms are developed using RCA developer, while reflection holograms use the CW-C2 developer. Both transmission and reflection holograms are bleached using EDTA bleach. This is followed by a slightly acidic stabilizing bath.

2.1 Laser and Table

The main equipment used in our laboratory is a green laser (500 mW, 532 nm, Continuous-Wave) and a vibration-isolated optical table (120 x 240 cm, 4 x 8 foot in size). On the table is a large plexiglass enclosure with doors, to limit air currents during exposure (shown in Fig. 1).

Figure 1. The optical table with an enclosure above to limit air currents. In this photograph, the enclosure doors are open, and they can be seen at the very top of the image (they are lifted up).

2.2 Setting Beam Ratio

The easiest way to set the intensity ratio between object and reference beams is with a variable attenuator. However, this wastes laser power, which is the reason why we don't use it. In order to keep the exposure times as short as possible, so that we can also record images from marginally stable objects, we use a half-wave plate on a rotation stage, followed by a polarizing beam splitter, and another fixed half-wave plate in one of the beams. This conserves more laser power, but is more difficult to adjust, because one changes both the object and reference beam intensities at once. To overcome this, we have built two wireless power meters, which use a Bluetooth (BLE) connection to a tablet that displays both readings. The power meters are mounted on adjustable magnetic bases, such that they can be installed in both beams, and both readings can be made at once. The tablet is mounted permanently above the table, where it is easily visible. There are also motorized (and remote-controlled) shutters in each beam, so that each beam can be turned on and off rapidly. The remote controls on the shutters are also a safety mechanism, because they eliminate the need to manipulate any beam blocks near the concentrated laser beams. Figure 2 shows images of the power meters, tablet and remote control for the shutters.

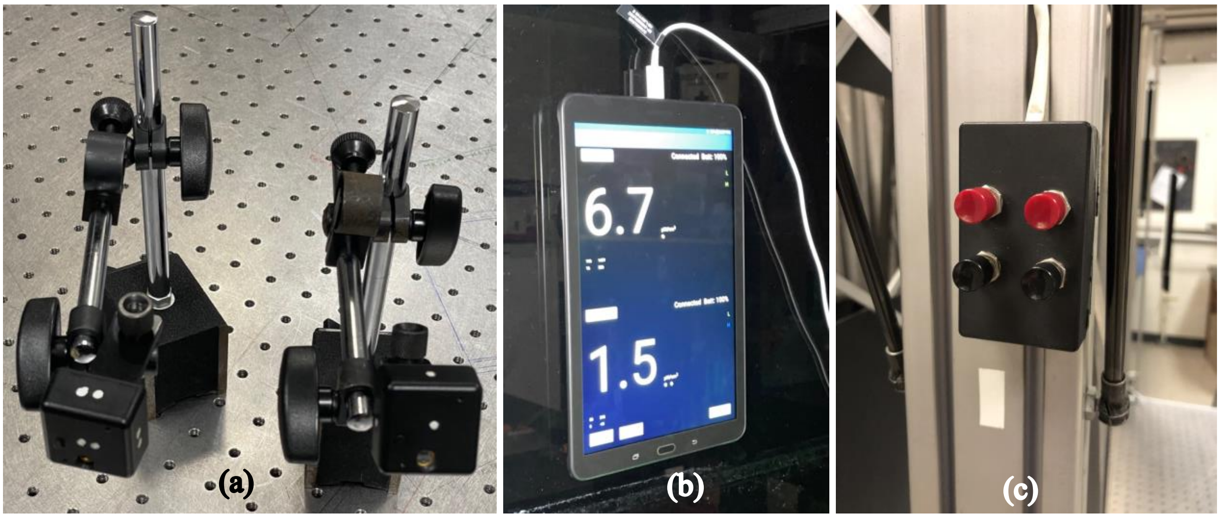


Figure 2. Equipment used to set beam ratio: (a) two wireless optical power meters, (b) a tablet mounted permanently above the optical table, showing the power meter readings, (c) remote control buttons for the two beam shutters.

In many cases, the two power meters can be placed in such a way that both measurements are made simultaneously, because no reference beam light enters the object beam power meter and vice-versa. Sometimes, however, this is not possible: both object and reference beam light enters both power meters. In this case, the remote-controlled shutters make it easy to quickly turn one beam off and then the other one, while adjusting the half-wave plate.

2.3 Spatial Filter Adjustment

The spatial filters are used to improve the quality of both the object and reference beams. They need to be set up and adjusted often. Especially the object beam spatial filter needs to be reinstalled for each hologram, because each team will choose a slightly different illumination angle and distance. The installation and adjustment of the spatial filter is the most advanced optical alignment procedure that the students are asked to perform, and it requires the close guidance of a teaching assistant with the necessary experience. In order to make the alignment simpler, we always keep all optical elements and all collimated laser beams at the same height. This way, no height adjustments of components is necessary, and beam height only needs to be fine-tuned by small amounts.

3. ANALOG HOLOGRAMS

The first student project is an analog master-transfer hologram. By analog, we mean a hologram produced from real-world objects, as opposed to the digital (synthetic) holograms described in the next section. Students must fabricate or collect the necessary objects to be recorded and bring them to the studio. They must consider the stability of these objects, as well as their brightness. They will often bring multiple related objects to make a multiple channel[7] hologram, in order to "tell a story.” Students must choose between a reflection and a rainbow hologram. In either case, the master is a transmission hologram.

In order to produce holograms that are reconstructed with illumination beams coming from above, students can choose between two alternatives: The first is to mount their subject sideways during recording, and work with a horizontal reference beam. This makes alignment easy, but it is more difficult to mount the subject. It has the advantage, however, that the object beam, which is also horizontal, will appear to illuminate the scene from above. The other alternative is to use a very tall and sturdy mirror mount (shown in Fig. 3) to bring the reference beam from above. Because the object beam is always horizontal, the scene will appear to be illuminated from the side, casting large shadows. Nevertheless, the vast majority of students chooses to use this mirror mount and keep the subject upright during shooting.

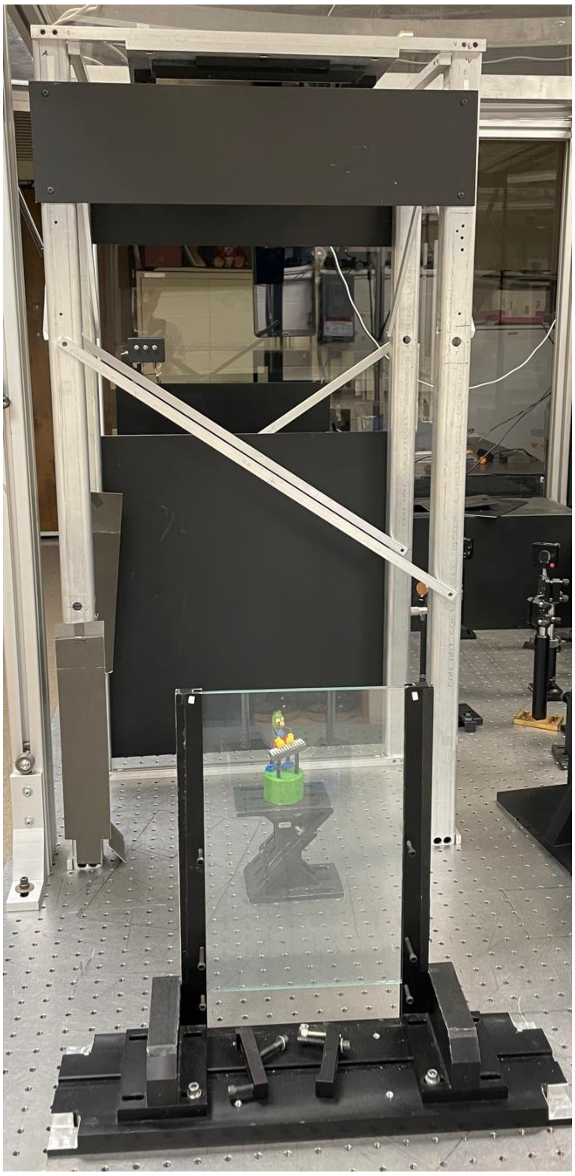


Figure 3. Tall mirror mount used to bring a reference beam from the top. A large mirror, facing down, is mounted at the top. The mount contains black shields to block unwanted scattered light.

For the master hologram, students must choose a subject-hologram distance. It needs to be fairly long, if they want to make a rainbow transfer later. They will also make adjustments to the scene illumination, but they cannot add additional illuminating beams.

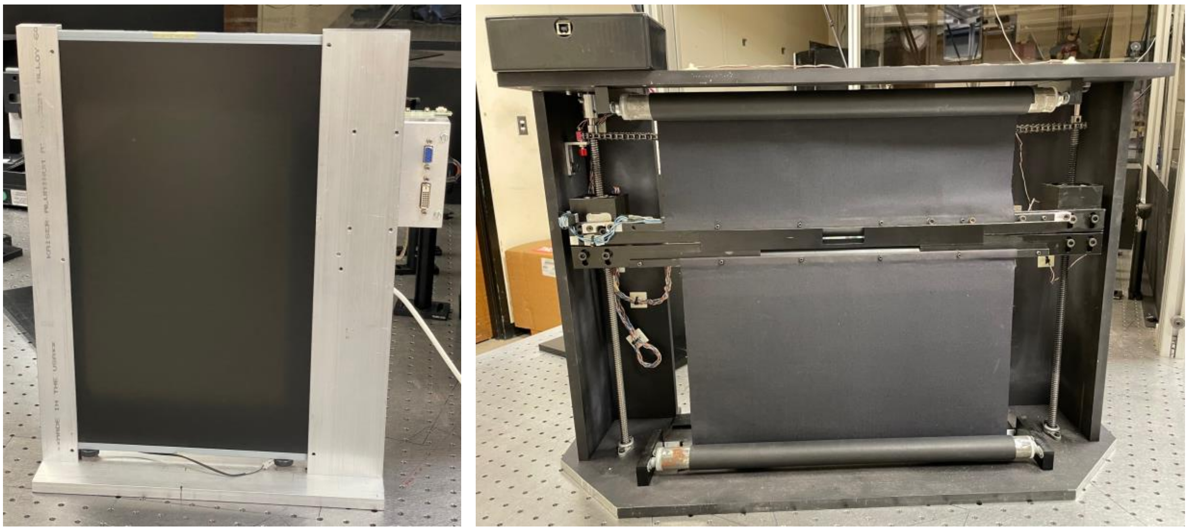
For the transfer hologram, the biggest choice is between a rainbow transmission or a green reflection hologram. Beyond this, they can adjust the master-transfer distance, in order to change how much of the subject is “sticking out” of the hologram.

4. DIGITAL HOLOGRAMS

The second project in the course is a digital hologram[8, 9], also called holographic stereogram. Here, the main tasks of the students are to prepare the digital content, and to record the transfer hologram. Recording the master hologram is done by the Teaching Assistant, since this step is very time consuming, and no adjustments are necessary.

The holograms in this project are pseudo-colour white-light transmission holograms which simultaneously record three rainbow holograms in the same transfer[10], such that from one viewing height, one of these rainbows will be visible in red, one in green and one in blue. At this ideal height, the image will appear in the correct colours. These are Horizontal-Parallax-Only (HPO) holograms, showing 120 different perspectives over an angular range from -18° to +18°. Students need to learn how to produce the necessary 120 two-dimensional image files.

We use an LCD screen, with the backlight removed so that laser light can pass through, to project the 120 images one after the other. The images are recorded into thin strips on the master plate, with the help of a moving slit assembly, which uncovers one strip on the master for each projected image. This produces a multiple channel hologram with 120 channels. To produce the colours, three such synthetic holograms (each composed of 120 channels) are recorded on each master plate. The hologram on one side of the plate contains the red information, the centre is for green, and on the other side is the blue component of the image. This means that a full hologram requires 360 exposures. For this, the moving slit assembly has one motor that moves the slit over 120 positions, and a second motor to uncover the correct colour channel. As is usual, the recording is done sideways, to allow us to use a horizontal reference beam, while the reconstruction beam in the finished hologram comes from the top. The LCD screen and moving slit assembly are shown in Fig. 4.



LCD Screen   Moving Slit Assembly

Figure 4. LCD Screen and Moving Slit Assembly, used to record digital master holograms. The moving slit can move up and down to record the 120 perspectives, while a cover in front of it moves left and right to select the red, green and blue channels. The recording is done sideways, to make it easier to produce top-illuminated holograms.

For correct colour reconstruction, the LCD screen and master plate are not parallel. Instead, they are arranged at the achromatic angle[11]. When producing the transfer, the master and transfer plates are again arranged at the achromatic angle. Fig. 5, shows the traditional transfer setup with the achromatic angle between the two holographic plates. The three colour channels receive different intensities of light, because of the difference in distance. Additionally, to shorten the master exposure time, for images that do not have equal intensity in each colour, we boost the weaker colour channels in software before exposing the master. This boost must be compensated by reducing the intensity when recording the transfer. The upshot is that we need a rapid and convenient method to adjust the intensity of each colour, when recording the transfer.

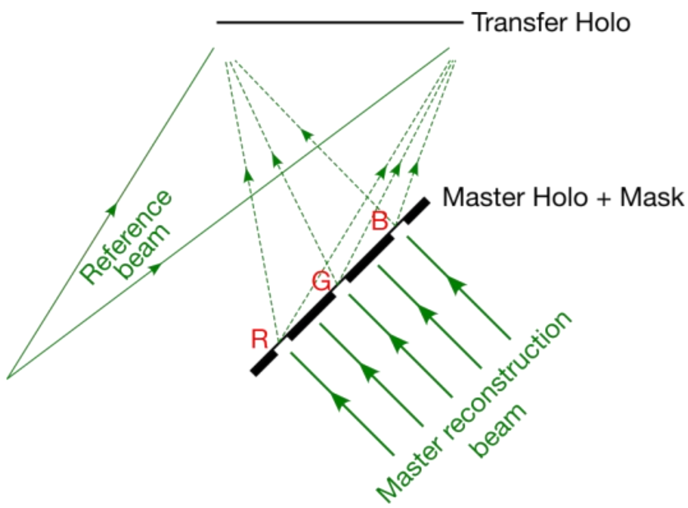


Figure 5. Typical transfer geometry for pseudo-colour white-light viewable transmission holograms. The master contains three rainbow holograms, one for each channel. The red channel is farthest from the transfer, while the blue channel is closest. Typically, a mask is applied to the master plate, which blocks light that would pass between the colour channels. We do not use this setup. Instead, we use the modified arrangement from Fig. 6.

In order to adjust easily the intensity of each colour channel, we use the setup shown in Fig. 7. This illuminates the three stripes on the master plate with vertical “lines” of light produced by a cylindrical lens. No masks are necessary on the master plate. The lines of light must have rays that are all parallel to each other, so a single cylindrical lens is placed at the focal point of a concave mirror, to expand all three beams at once. Before passing through the lens, the three concentrated beams pass through an assembly of three variable attenuators, which can adjust the intensity very easily. As a safety feature, the variable attenuators are motorized, so that we don’t have to handle components near the concentrated laser beams.

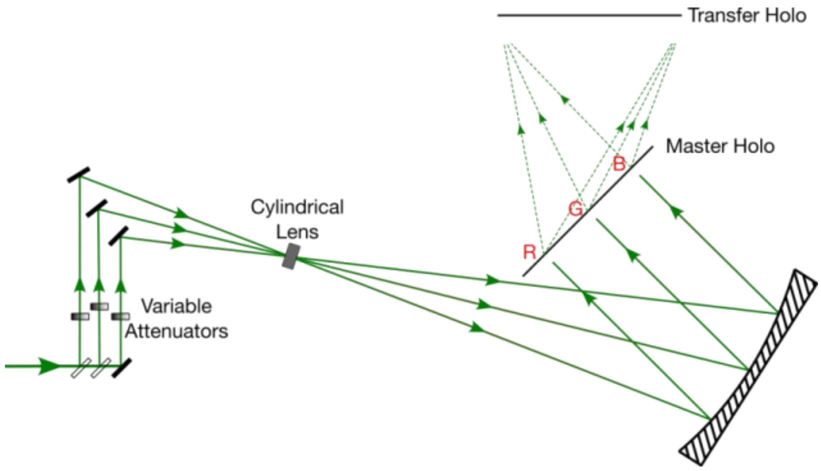


Figure 6. The transfer geometry for pseudo-colour white-light viewable transmission holograms used in our studio. On the left we start with one concentrated laser beam, which is separated into three beams by beam splitters. The intensity of each of the beams is adjusted individually, with variable attenuators. The beams then “meet again” in a cylindrical lens, which expands them into vertical “lines” of light (in and out of the page). These are then collimated by a concave mirror and sent into the three colour sections of the master hologram. For simplicity, the reference for recording the transfer is not shown, but is identical to the reference beam from Fig. 5.

5. CONCLUSIONS

With the equipment and techniques described in this paper, we are able to offer a hands-on holography experience to students who have never manipulated optical elements. Most students record a hologram of reasonable quality on their first try, while also focusing on the artistic content. By making the process of recording holograms more efficient and reliable, more students can take advantage of the holography course and holography studio at the University of Toronto. In designing the equipment and procedures, we tried to provide enough flexibility for students to adjust light beams as needed for their individual holograms. At the same time, we insist that they follow some general layouts that are prescribed ahead of time, which are known to work.

The work in the holography studio helps students understand many optical physics phenomena, such as interference, diffraction, light propagation, etc. They do this while also developing the artistic concept of their hologram. In today's world, most creative work is done and presented on a computer. Working with physical objects and chemicals in order to produce 3D images which must be experienced in person (without a computer) is a refreshing activity. As a result, our holography activities are very successful, earning very good reviews from the students.

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Teaching hands-on the science and art of holography

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ABSTRACT

Many holography courses focus either on artistic and visual aspects of holograms, or on scientific principles for recording images via interference. Here we describe a unique undergraduate course at the University of Toronto, that covers both the science and the art of holography. Students learn the necessary optical physics, while completing holographic art projects. The course evolved out of research collaborations between optical scientists and holography artists. It is a breadth course for students from many disciplines. Holography gives highly visual demonstrations of many optical physics effects, including interference, diffraction, coherence, polarization. At the same time, students learn to propose, execute, present and critique an art project, and learn about key developments in visualization, and artists' previous work in holography. Projects are done in interdisciplinary teams which consist of two students who come from different programs of study. This allows them to learn to work with someone from a different discipline. They also support each other with the very interdisciplinary course content. In their teams, students first produce a real-world-object hologram (either reflection or rainbow), through the master-transfer process. Their second hologram is produced from a digital 3D graphics model, that is printed as a full-colour white-light transmission hologram. The holograms are graded both on the strength of the concept, and on the technical execution. Students rate this course very highly. In this paper we describe the course, including learning outcomes, content and organization, and the kind of work students perform in the holography studio.

Keywords: Undergraduate course, optics, art, collaboration

1. INTRODUCTION

The University of Toronto offers a holography[1] course as a breadth option[2], which uses the medium of holography to teach concepts of both optical science and of holographic art. Students must complete two projects in this course by working hands-on in a laboratory to produce holograms. This is complemented by standard classroom lectures.

The students in this course are undergraduates from a wide variety of programs from the Arts and Humanities, Social Sciences, Life Science, Mathematical and Physical Science, Computer Science, Architecture and Engineering. While they may have heard a few things about holography, they generally have very little knowledge about the subject, and have not produced any holograms before. They also have no experience handling laser beams and optical laboratory equipment. Each year, a small number of students have some experience proposing and executing art projects, but the majority do not. Even though holography is relatively unknown to most students, it is also a mysterious and intriguing subject, which serves as an excellent motivator. Therefore, the medium of holography is an ideal starting point for learning optical physics and the production of art projects.

This course has evolved out of research collaborations between optical scientists and holographic artists in Toronto in the 1990s and 2000s, which has resulted in the joint construction of several pieces of apparatus for the professional production of digital display holograms, as well as general troubleshooting of problems with the recording of many kinds of holograms. Some of the apparatus used by the undergraduate course is based on simplified versions of the research-grade equipment produced by that collaboration. In keeping with the lessons learned from the research collaboration, the teaching in the course presented here has been delivered for many years by a team composed of a science and an art instructor.

The course is now part of the Creative Expression and Society program at Victoria College (See Fig. 1). This program encourages students to explore creativity in a wide range of media and genres including literature and poetry, visual arts, music, etc.

Figure . Victoria College at the University of Toronto, where this course is offered.

2. COURSE STRUCTURE

The learning in the holography course presented here consists of three major components: classroom lectures with associated tests and assignments; studio teaching, where the production of holograms is demonstrated; and the projects which are executed in widely interdisciplinary teams.

2.1 Classroom Learning

The classroom time is used to cover the theoretical material necessary for understanding the science of holography and human visual perception, as well as history of visualization and artists' past work in holography.

On the science side, classroom material includes the fundamentals of optics, such as wave propagation, interference, diffraction, polarization and coherence. A lecture is also reserved for understanding the chemistry of holographic film, and the processes of exposure, development and bleaching. Based on these basic concepts, we explain the recording and reconstruction of holograms, including thin (transmission) and thick (reflection) holograms, as well as the master-transfer process. We also discuss holograms that can be displayed with incoherent light (reflection and rainbow holograms)[3].

Because this is an introductory course, we base much of the explanation of holography on the basic idea that the reference beam is used to record the location, direction, intensity and phase of individual rays coming from an object. Using a copy of this reference beam one can reconstruct an identical copy of the recorded light rays at playback time. The holograms are presented as a "window with memory" that record and play back all the light rays going through them This concept of a window is also used to understand the parallax limitations in master-transfer holograms, by considering the "window of the master hologram" that limits the angles of rays available for recording into the transfer hologram.

The next step in the technology of holography is to understand digital holograms, sometimes also called synthetic holograms. First we cover master-transfer digital holograms, such as those introduced by King et al[4]. Combining these with the ideas of rainbow[5] and achromatic[6] holograms, we introduce pseudo-colour white-light-viewable transmission holograms[7]. Students need a good understanding of these, because their second project is based on them. Although we do not produce them in our facilities, we also describe in the lectures the direct-write digital holography process.

While the main topics in this course relate to display holography, we also introduce some additional technical uses of interference and holography for non-destructive testing, digital holographic microscopy and high-sensitivity measurements. Near the beginning of the course, we also devote one class to laser safety training, which is essential before students are allowed to use the laser lab.

On the visualization and art history side, we start with a history of visualization, from the early experiments of Edweard Muybrdige to today. Emphasis is placed on methods and techniques that make it possible to see phenomena that are too fast or too small to be observed directly. We also provide a history of technology used for 3D (depth perception) including head-mounted displays and other immersive environments.

A lecture is devoted to past artists' work in holographic installations. This includes early work with real-world objects, as well as newer work with digital holograms, including methods for content acquisition with camera arrays or moving cameras. We cover the work of artists such as M. Benyon, H. Casdin-Silver, R. Berkhout, J. Desbiens, M. Page, etc. A challenge here is the fact that we do not have direct physical access to most important holograms that we discuss. Relying on 2D photographs or 2D video does not convey the full depth perception of the original holograms. The survey of past work includes mixed-media installations that combine holography with painting or drawing, as well as non-representational imagery which takes advantage of the vivid, saturated colours produced by diffraction of white light in transmission holograms.

For human perception, we focus on both the perception of colour and depth. For colour perception we describe the physiology of vision, including the three kinds of wavelength-sensitive photoreceptive cone cells, and explain how the human visual system is able to perceive millions of different colour hues based on only 3 types of cones. Based on this understanding we introduce the principles of RGB colour displays. Because many students in the course are more familiar with the subtractive model of colour combination, we need to clarify when the production of colours is based on additive and when on subtractive combinations of colours.

For depth perception, we introduce the main monocular and binocular depth cues. We need to emphasize that holograms exploit many monocular cues, such as motion parallax, even though in the popular media the binocular cues are mentioned almost exclusively.

2.2 Learning in the Studio

Throughout the term, we hold four demonstrations in the holography studio, or laboratory (Fig 2). In these sessions, the process of creating various kinds of holograms is demonstrated and explained. Although at our university most teaching is done in a classroom, it is advantageous to teach the practical aspects of making holograms in the studio, in the presence of the equipment. In these sessions, the instructor records a hologram, with the assistance of the entire class, while explaining all the steps. Almost all the holograms demonstrated are of the same kind as those that will be required in the projects. Because this course places as much emphasis on the content of the holograms as it does on the process, students are encouraged to contribute to the content of these holograms as well: at the beginning of the session, students are invited to make a very quick proposal for the content, and often a group of students will spontaneously produce an unusual and creative idea.

Figure 2. The optical table where the demonstrations are held, and where students work on their projects.

In the first session, we demonstrate real-world-object master holograms. This is the most important session for understanding holography, because here we explain the basic principles of using a reference beam to record light coming from the object and we demonstrate how the same reference beam acts to reconstruct the image in the original location. Because this is the first time in the studio, we must start by explaining basic principles of optical alignment, such as the fastening of mirrors to optical tables, using adjustment screws to aim beams, etc. Before starting with the hologram, we also explain the principles of laser safety used in this course.

The second session introduces the transfer holograms. Here we demonstrate both a reflection and a rainbow transfer, and discuss the benefits and drawbacks of each. At the same time, we discuss pseudoscopic images, as well as the tradeoffs incurred if one pushes the image too far in front of the holographic plate. We show how multiple-channel holograms are produced, and discuss ways to take advantage of this technique to convey a message. Together, the first two sessions cover the techniques necessary for completing the first project.

The third session introduces digital holograms, recorded from a frame stack of 120 two-dimensional images. This involves more pieces of equipment[8]: (a) an LCD screen modified to allow laser light to pass through it, which projects the individual images from the computer; (b) a moving slit assembly, which records each two-dimensional image into a narrow strip on the master hologram. Before recording the hologram, we discuss how this apparatus allows the final hologram to project each individual two-dimensional image in a different direction, and why viewers interpret this as a 3D image. With the master hologram recorded, the students can convince themselves that the image does indeed look three-dimensional. We then record a reflection transfer hologram from this master. Because the frame stack of two-dimensional images can include some small amount of motion in the subject, we discuss the trade-offs between this motion and the perception of depth.

The final studio session demonstrates pseudo-colour white light transmission holograms, of the kind that the students will produce in their second project. These are digital holograms using the same equipment for recording the master as in the previous studio session. However, we arrange the holograms at the achromatic angle[6], and record three narrow stripes on the master plate for the three colour channels[7], to produce the full-colour hologram. These holograms act as a superposition of three rainbow holograms. At the proper viewing height, one of them will appear in red, one in green, and one in blue. The main discussion during this session is centered on understanding the principles through which the colours are obtained. Recording the master is a very slow process, because 360 exposures need to be made. Therefore, we set everything up, but do not actually do the recording during the session. Instead, we show a pre-recorded hologram. Then we set up for the transfer, and produce the resulting transfer hologram with the students.

2.3 Projects

During the projects, students are expected to propose, execute, present (providing rationale and motivation) and critique artistic holograms. Because this is an interdisciplinary course, we ask students to work in interdisciplinary teams of size two. As this course started out originally from the collaboration of optics researchers with holography artists, the initial plan for the student teams was to pair up a physics student with a fine art student. Since, however, most students in this course study neither physics nor fine art, we insist instead that they find a partner from a discipline very different from their own. For example, an architecture student might work with a computer science student, or an English student might collaborate with a life science student. This interdisciplinary collaboration contributes to the learning goals of the course: Besides the classroom and studio teaching, we would like students to learn from their partners. Those from other disciplines generally have other approaches to their work and other areas of knowledge, and it is very useful for students to work across the disciplines. Especially for the creativity needed in an art project, discussing with someone of a different background can be very beneficial, even if that person is not an experienced artist.

Because most students have never participated in such a project before, we start with a project ideas workshop, where each team has to present its plans for the hologram in front of the class. They receive feedback, suggestions for improvement, and related ideas from the teaching team and from the rest of the class. They then submit a written proposal, explaining both the concept or premise of the work and the way they intend to execute it.

Once the proposal is approved by the teaching staff, the students will schedule times with the teaching assistant when they will record their hologram. To reduce the time needed for optical alignment for the first project, based on real-world-object (analog) holograms, we try to schedule multiple teams for the master first, and only afterwards rearrange the table for the transfer. For the second project, based on digital holograms, the Teaching Assistant will record the master without the students present, because this is a slow process and there are no adjustments or alignment steps for the students to do.

During the execution of the project, students will often refine or adjust the concept of the work. They will do this as they collect the material to be recorded, while aligning the laser beams, or even after the hologram is finished. Often, one of the objects in the analog hologram will be unstable and disappear from the image, which sometimes changes the meaning of the work.

Finally, the holograms are presented to the class in a critiquing session. The holograms are displayed one by one, and each team presents their goals of the work and an assessment of their success. Feedback is again invited from the rest of the class. During these critiquing sessions, students have the opportunity to closely examine many student holograms.

In assigning grades for the project holograms, the concept and execution and weighted equally. That means that for a high grade, a hologram must have a strong concept, and be well executed. Under execution we understand the choice of objects that will give a visual representation of the concept, as well as the actual success in recording a hologram. However, holograms that are dim are not penalized, because the efficiency of the recorded images is often not under the students' control, especially when they can only make a single hologram.

Many students have produced impressive holograms in their projects. This has allowed us to organize a few exhibitions of holograms, including one at the University of Toronto Art Centre. See Figs. 3-5 for examples.

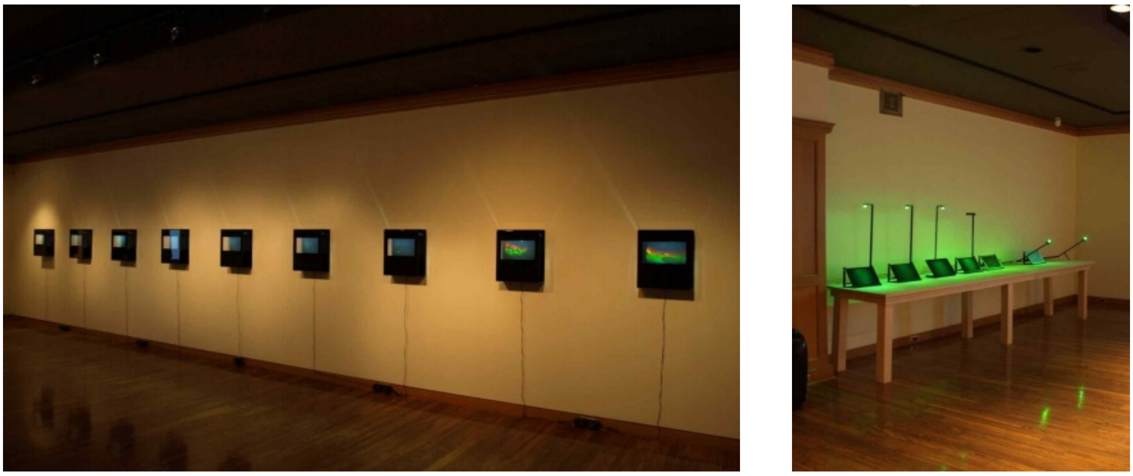

Figure 3. Student holograms exhibited at the University of Toronto Art Centre.

3. MAIN CHALLENGES

This is a very unusual course for our university. Such detailed studio work where students are expected to produce art, followed by a critiquing session is more usual for an art college than for a large research university. Therefore, many aspects of the course organization are different from other courses at our institution.

This is also a very expensive course, in terms of equipment and consumables, and in terms of the time required of the teaching staff. Because of this, we can only provide a single optical table and laser to the students, which makes scheduling of studio time before the project deadline more difficult. Also, the nature of holography requires very close attention from the teaching assistant, while the students work in the studio. Finally, it is very important to improve the reliability of the holography process, so that most students can produce a hologram of reasonable quality on their first try In our studio we have introduced a number of new techniques to help make the process of holography more efficient and reliable[8].

A further challenge has to do with the amount of time in a term and the material that must be covered. Our goal is to give students a reasonable introduction to both the art and the science of holography. This means that lectures must progress at a rapid pace. Besides the projects described here, students must also complete tests and assignments on the science questions. In order to be able to accommodate two projects during the 12-week course, we need to start very early in the course with the team formation, and the project proposals come quite early too.

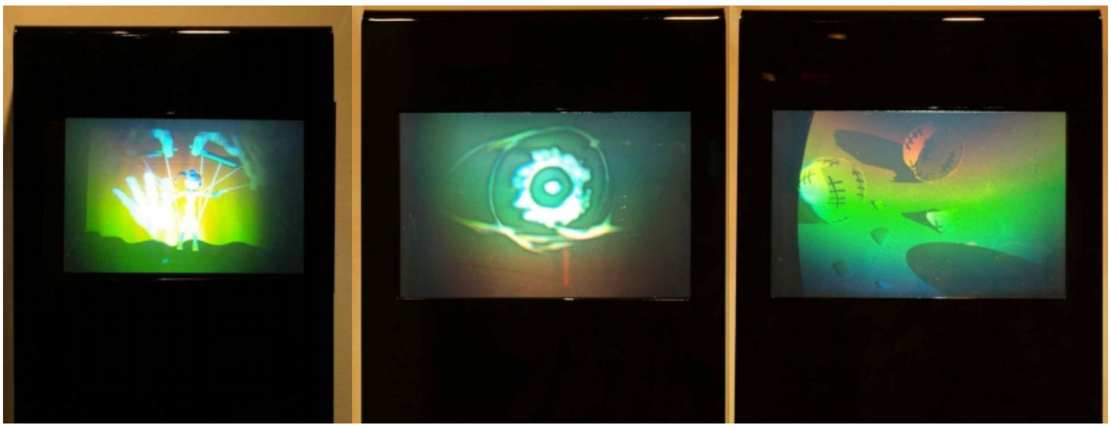

Figure 4. Examples of transmission holograms produced by students. (Left and middle holograms are digital. On the right is a rainbow hologram.)

Figure 5. Examples of reflection holograms produced by students.

Such a widely interdisciplinary course is not common at our institution. Although students end up appreciating the opportunity to work with students from vastly different backgrounds, everyone must make an effort for such collaborations to be successful. In order to accommodate all the students, we must explain the science without any equations, and we must also be mindful that most science students have little experience completing art projects.

4. CONCLUSIONS

The holography course described here is a very unique offering at our university. Despite the challenges described above, it is a very successful course, because students appreciate very highly the opportunity to take part in such a unique activity. The concept of holography is still very mysterious to most students, which attracts them and motivates them to put in the necessary effort for the course. As a result, students produce excellent work. The subject of holography helps students understand a very wide range of topics in optical physics, such as wave propagation, interference, diffraction, coherence, and others. It is also a good way to introduce students to the execution of art projects.

In today's always-connected world, much work is done on a computer screen. In particular, most assignments in most courses are submitted digitally, through a course website. Holography requires students to do hands-on work manipulating physical objects in a dedicated studio, which includes developing the holograms in chemical baths. While computers are necessary for the production of the 3D content for the digital holograms, that is only a part of the holographic process, and the end result is a physical object. This hands-on work away from a computer is a very welcome activity today. It is not surprising that such a holography is highly rated by students. Each year there are multiple students who call this course their best experience at university.

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Art and new media: visual information recording for digital art holograms in higher education context

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ABSTRACT

In this paper we are presenting and discussing several artistic concepts and movies created in art in higher education context, in the discipline of Art and New Media. These movies are the visual information for printing digital reflection holograms according to the CHIMERA™ half-parallax video captures instructions.
This Art and New Media subject is part of the first semester of the 2022-2023 academic year, of the 3rd year of the Art and Design Course, at the Education School of Coimbra, belonging to the Polytechnic Institute of Coimbra, in Portugal, and was the first time it was taught.
Some of the objectives of that discipline are to develop skills in multidisciplinary artistic practice; new media in expressive contexts, which one of this new media is holography; creation of sensorial environments and interactive installations.
Thanks to the opportunity of the ISDH 2023 Contest, some of these movies were created and submitted, with the aim of having them printed by CHIMERA™, if selected.

Keywords: Art and New Media, video capture, digital art holograms, holographic space, movement, interaction

1. INTRODUCTION

Art and New Media encompasses many different approaches to making art, at different stages of creation, production and/or presentation, using the new technologies of the digital age, such as computer-based art, digital photography, digital holography, electronic music, interactive installation art and projects that employ virtual or augmented reality, offering new ways of thinking and experiencing art.

Holography has been used in the creation of visual art, enabling works that reflect the renewal of the aesthetic experience For example, considering holograms and holographic image, the fact that holograms are always printed on a holographic plate, but the holographic image can float in the space in front of the holographic plate, in the space behind that plate, or in both simultaneously. Several images can be observed from different points of view.[1]

According Edward Lucie-Smith, holography probably followed the same path as photography and video, which is to be used not for its own sake, but as a creative element[2]. Frank Popper[3] said that artistic holography allowed for a new development in the aesthetics of absence; the holographic image is one of the images most linked to the phantasmagoria of the immaterial[4], an image that reveals itself depending on the interaction of the observer. Liquid, ethereal image, which has the floating consistency of an organic substance. The multiplicity of space and time, the sensation of presence and absence of the holographic image, as well as the relationships of light and colour of high purity and brightness, allow a new way of understanding the malleability of space, through the plasticity of light[5].

Therefore, the justification for holographic representation lies in the intricate web of rationality that unfolds from informational factors, allowing it to be extracted from physical reality and transcended into the virtual realm of time and space. Although its support is tangible and perceptible, it subtly dissipates, tightening the bonds between space and representation, and between this and the viewer.[6]

In this article, we will contextualize holography in Portugal, how digital holography was integrated in the context of artistic higher education and, consequently, about the work done by the students.

2. ABOUT HOLOGRAPHY IN PORTUGAL - CONTEXT

The development of holography in Portugal has taken place in different laboratories located at University of Porto, University of Aveiro, research centres and institutes: CLOQ (Centro de Lasers e Óptica Quântica), INETI (Instituto Nacional de Engenharia e Tecnologia Industrial) and in a state printing company INCM (Imprensa Nacional Casa da Moeda). The research and development activities are supported by National and European programs and projects involving national and international partners.

The holographic principles and technologies are taught in graduate and undergraduate courses at the Universities of Porto, Aveiro and Lisboa. Summer schools, seminars, talks and exhibitions are organized regularly to the specialists and the public in general. The Science Museum of University of Porto, the Science Centre the "Fábrica", connected with University of Aveiro, and programs like "Ciência Viva", are all strongly promoting that kind of actions. One of the strongest is the implementation of a network of basic holographic labs in schools.

The HOLOLOB – Holography Laboratory, is installed at the Science Centre the "Fábrica", "Ciência Viva", at the University of Aveiro, "it is a laboratory where visitors can explore and experiment with holographic techniques. In this space it is possible to record 3D holograms through the manipulation of LASER light, mirrors and other optical components or simply draw a hologram by hand"[7].

Some work in Art Holography has been done at University of Porto and at University of Aveiro. The teams were composed by physicists and artists and their objective was to obtain transmission and reflection holograms to be reconstructed with laser or white light. Rainbow holograms and multiple image holograms have been more deeply researched. Colour control on reflection holography has been obtained by means of chemical methods, other than the preswelling on silver halide photographic emulsions. In 2012, University of Porto has produced a transmission hologram with a reconstruction of seven meters' depth. Collaboration between University of Porto and De Montfort University, Leicester, UK, since 2011 carry out developments in digital art holography. The holographic artistic work produced has been showed in international conferences as well as in international artistic context.

But when we refer to the teaching of digital artistic holography in Portugal, it was in fact in this first semester of the academic year 2022-2023 of the 3rd year of the Art and Design Course, at the Coimbra Education School, Polytechnic Institute of Coimbra, which was the first time taught, integrated in the discipline of Art and New Media.

3. CONSIDERATIONS ABOUT STUDENT CLASSES

Some of the objectives of the Art and New Media discipline are to develop skills in multidisciplinary artistic practice; new media in expressive contexts, where one of these new media being holography.

The classes took place with oral exposition centred on the foreseen contents. Specifically in relation to analogue and digital holography, basic principles and methods of capturing image information were taught. A study and presentation of works/productions was carried out - various types of holograms were shown, such as the artistic digital holograms produced by Maria Isabel Azevedo, one of the authors of this article, during the collaboration between the University of Porto and De Montfort University, in a postdoctoral program funded by the Fundação para a Ciência e a Tecnologia. And then we moved on to the planning and development of projects aimed at digital holography, in which students were divided into work groups based on the investigation of a theme.

With the announcement that, as part of the ISDH 2023 – 12th International Symposium on Display Holography, there would be a Contest, in which projects for recording image information would be printed on the CHIMERA™, student projects were then created and submitted to the competition, proposed to be printed as digital reflection holograms, if selected.

4. IMAGE INFORMATION RECORDING TECHNIQUES

In a broader context, holography is the technique for recording image information. In the case of digital holography, the use of the laser is not necessary during the creation phase, as image information is recorded primarily from a variety of video recordings, Cinema 4D, 3D Studio Max, 3D CAD programs, Maya, in addition to 3D image scanner programs and then printed, using lasers that record the image information on a holographic plate sensitive to laser light, and respective chemical processing, with development and fixation baths. After the printed hologram has been chemically developed, the holographic image can be viewed with white light.[8]

There are also image capture systems for producing holograms of living beings and landscapes, such as the HoloCam Portable Light System, which produces a digital photo/video sequence in the so-called HPO format (horizontal parallax only) for holographic printers Syn4Ds, from the company Geola Digital uab, in Vilnius in Lithuania.[9]

There is also the Chimera™ 3D holographic printer in Bordeaux, France[10]. It is a mechanism patented by Yves Gentet and intended to produce the new generation of digital holograms. He also names the digital holograms produced there by the name Chimera™. The data comes from a 3D capture of a real object or from computer generated objects using 3D software (such as 3DSmax). This data is used to calculate a hologram that is printed pixel by pixel (called "hogels") using RGB lasers and holographic recording material known as Ultimate Uo4, also developed in this company.

Holograms are always printed on a holographic plate, whether they are created by analogue processes or using digital processes.

5. VIDEO RECORDING

To record the image information, which could become holographic images, activities were carried out in one of the studios at the Centre for Informatics and Audio-visual Media, at the Coimbra Education School, using the Chroma-Key technique.

Chimera™ half parallax video capture instructions[11] were followed. Viewpoints of the scene were recorded on a 120° arc of a circle by rotating the scene and keeping the video camera static. The distance from the camera to the centre of rotation varied according to the students' proposals, between 60 cm and 1.20 meters; the camera was oriented vertically. According to the instructions, the centre of the scene rotation will be the vertical axis of the final Chimera™. Any scene element in front of this centre will appear "floating" in front of the Chimera™ (the glass plate). HD video format was used: 1080x1920, which is recommended for hogel printing 30x40 Chimera™ 500µm (cropped to 660x660).

The recordings made in the studio were later edited in the programs Adobe Premiere Pro and Adobe After Effects, allowing several scenes to be placed within an image. The thought of the final result in the form of a holographic image and the position of the viewer in front of it crossed the entire process of creation and production of these projects. These videos were then sent to the ISDH 2023 Contest.

As previously mentioned, the students worked in groups and each group developed a concept and a video, which is the proposed image information to be printed as digital reflection hologram. Some frames of these videos are presented in point 6., from Figure 1 to Figure 7, as well as the summary that each group wrote about each concept developed, and then a brief reflection on each work.

6. ART CONCEPTS AND IMAGE INFORMATION TO RECORD

“Mystical fire” (Fig. 1), project by Ana Raquel Mendes, Mariana Mendonça and Patrícia Lemos.

“The concept of our project focuses on the representation of one of nature's elements, the fire.
We thought the best way to bring the concept to life was to create a dark and mystical environment, inspired by the Harry Potter films.
Fire being an element with a lot of movement, we chose to demonstrate this movement through the books that hover in the air and their pages that move by themselves, also symbolizing the mystique of our concept.”

In this project, the students dedicated themselves to the representation of one of the most powerful and intrinsic elements of nature: fire. Recognizing the importance of bringing this concept to life in a captivating and engaging way, they chose to work on the dynamics of fire, from a unique approach.

The books suspended in the air, with their dancing pages, personify the fluidity and energy contained in fire. This symbolic choice not only portrays the movement of this element, but also evokes the aura of mystery and magic that permeates the concept.

When conceiving the work “Mystical Fire”, they aspire to transcend the limits of the material world, plunging into a realm where imagination and spirituality harmoniously merge. Through this unique sensory experience, they seek to instigate reflections on the duality of fire: its ability to create and destroy, to heat and purify. By awakening the mystique of fire, the intention is to provide an artistic experience that awakens curiosity and incites a deeper connection with nature and its elemental forces.

Figure 1. “Mystical fire”

“Fim dos sonhos” (Fig. 2), project by Beatriz Tejo, Leonardo Rama, Mafalda Machado and Sílvia Dias.

“The concept behind our hologram reflects on the end of our innocent imagination as children. An age where everything is possible, enchanted and perfect. A world different from the real one, where fairies and other purely fictional magical creatures can exist, because when we are children there are no barriers to our fertile imagination. However, as we grow, this magical world that our imagination has created, stops making sense and we stop believing in it. What our hologram intends to represent is the sadness that these magical beings feel because we no longer dream of them. In our hologram we can see a lonely fairy crying in a dark setting, which once had been an enchanted forest.”

The "Fim dos Sonhos" project is based on a profound concept that hides behind a hologram, provoking reflections on the twilight of the innocent imagination that we nurture in childhood. In this enchanted phase, everything is revealed to be possible, a perfect kingdom where fairies and magical beings dance in the vast horizon of our fertile fantasy, unscathed by the boundaries of reality.

However, as we climb the path of maturity, this enchanted world that we engender loses its charm, and we, in our fading naivety, stop believing in it. It is this anguish that the students seek to embody through their hologram: the intimate sadness that magical beings experience when they perceive us already devoid of dreams about their existence.

This holographic projection grants us the vision of a lonely fairy, tears pouring from her eyes in a somber setting that was once an enchanted forest. In this image, we capture the essence of desolation and melancholy, an eloquent visual testimony to the waning of our connection with the imaginary universe.

By delving into the theme "Fim dos Sonhos ", we not only aim to evoke deep feelings, but also intend to incite the observer to contemplate the gradual loss of the ability to dream and fantasize, as we move away from youth. Through this artistic representation, they praise the objective of awakening sensitivity and understanding about the importance of preserving magic and creativity in our lives, even when faced with the challenges and responsibilities imposed by the adult journey.

Figure 2. “Fim dos sonhos”

“Dream in the flow” (Fig. 3), project by Carolina Remígio, Catarina Milheiro and José Faria.

“This hologram represents our idealized calm, serene and magical places where our child spirit is awakened with happiness and freedom.

We were inspired by some dreams we had, thoughts and idealizations of reality. Here, we remain calm with the magic of colours and natural elements such as mushrooms, the forest and fireflies flying over the environment.
This is an expression of our magical world.”

The "Dream in the Flow" project materializes serene and magical scenarios in which the spirit of a child awakens a state of happiness and freedom. Students are inspired by vivid dreams, fleeting thoughts and glimpses of a transcendent reality Students are inspired by vivid dreams, fleeting thoughts and glimpses of a transcendent reality. Here, immersed in this serene atmosphere, we find refuge in the magic of vibrant colours and in the natural elements that make up our enchanted vision: mushrooms, the exuberance of the forest and fireflies that dance harmoniously around the environment.

This is a living portrait of our magical universe, a visual expression that overflows with the beauty and fascination that permeate our daydreams. In "Dream in the Flow", we invite the viewer to delve into this dreamlike dimension and rediscover the purity and wonder that inhabit each of us. It is an invitation to contemplation, introspection and reencounter with the innocence and imagination that once captivated us.

In this magical world we create, we want to awaken a sense of belonging and enchantment, reaffirming the importance of preserving a space where fantasy and creativity can flourish freely. By immersing ourselves in this paradisiacal vision, we are invited to rescue the connection with our inner child and rekindle the flame of imagination that sometimes fades away in the routine of the adult world. In short, "Dream in the Flow" is an ode to the magic that permeates our dreams and the eternal ability to believe in the extraordinary, even when faced with the harshness of reality. In this work, we celebrate the transforming power of the imagination, and the vital need to cultivate a space where we can get lost and, at the same time, find ourselves in the enchanting simplicity of a world that can only exist in our dreams.

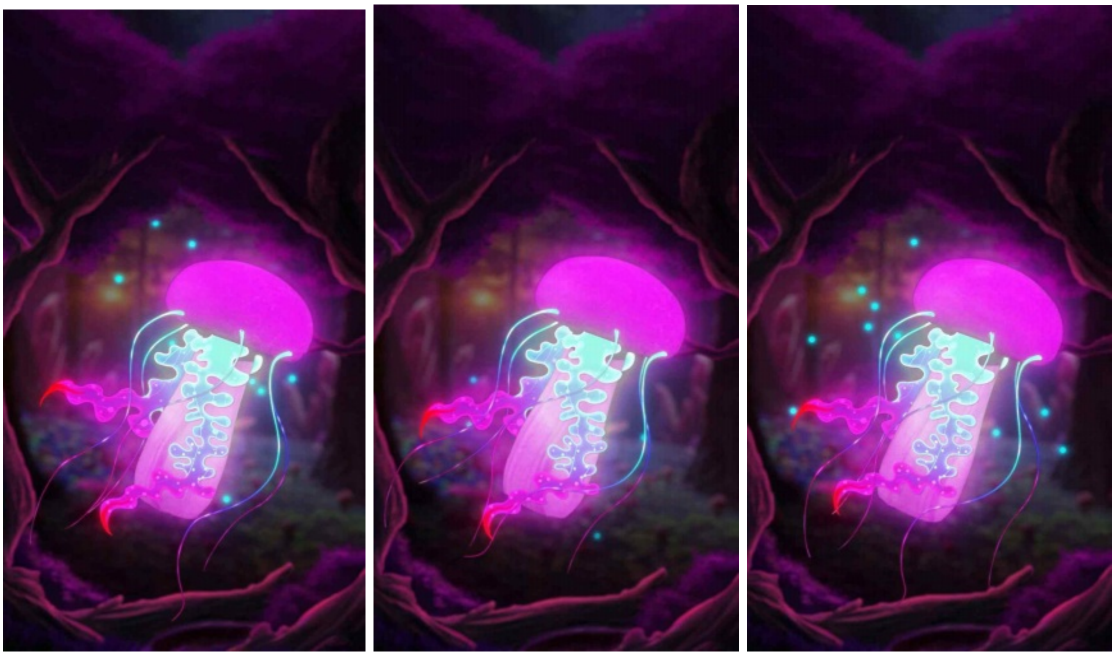

Figure 3. “Dream in the flow”

“Busca” (Fig. 4), project by Diogo Ferreira and Miguel Rodrigues.

“It portrays the search for love and the emotion we can be in when we find it. The characters are naked, just wrapped in a cloth, thus showing their innocence. They wear a crown of thorns that portrays the suffering they are feeling for being in search of love. Both “pray” to a beating heart as it hovers above their heads. The background presents a dark forest that expresses the feelings of the characters: they are lost and afraid.
When the characters touch their hands, a sign of love meeting, they make the background change, thus representing both the fire that a new love can bring us, the joy and agitation or also the despair, sadness and agony that leaves us as in hell.”

At the heart of the "Busca" project, the plot of the tireless search for love and the state that the encounter of this feeling brings us is revealed. The protagonists, naked and wrapped only in a veil, reveal themselves in their purest and most innocent essence. Adorned with crowns of thorns, symbolizing the martyrdom inherent in the search for love, they bow in prayer before a beating heart, suspended majestically above their heads. Enveloping them, an enigmatic and somber setting of a forest echoes the most intimate yearnings of the characters, where the feeling of doom and fear are subtly intertwined.

The moment their hands meet, signalling the link of love, a metamorphosis takes place in the background, capturing the range of emotions that this union is capable of awakening. The scenery changes, revealing the incandescence of the fire that a newly discovered love can ignite, with its load of joy and frenzy, or else the agonies, sadness and despair that consume us, as if imprisoned in an intimate hell.

"Busca" dives into the most unfathomable depths of human search for love, revealing the intricate duality that permeates this highly exalted feeling. It invites us to a deep reflection on the worries, sacrifices and sublime moments that accompany this incessant search for connection and emotional fulfilment. By revealing the multiple facets of this fervent yearning, we are prompted to question the very nature of love and confront the universal truths that unfold in this burning quest.

Figure 4. “Busca”

“Desconcerto do pensamento” (Fig. 5), project by Bárbara Monteiro, Carolina Guimarães, Catarina Chico and Humberto Costa.

“You walk around aimlessly and without meaning. You don't know the whys or what to feel.
We decided to represent a character in circles, as a result of his inner confusion. The feet and eyes that mean walking and seeing as what moves us forward. The change, the turnaround and a pensive attitude that, without reaching a consensus, makes us sad and objects to the environment.
In this sense, we represent the bewilderment of thought that anguishes lives and often prevents us from moving forward, remaining only in circles, in a constant whirl.”

The project "Desconcerto do Pensamento" dives into the depths of internal confusion, where we wander aimlessly and without meaning, wrapped in a fog of uncertainty. The central character, in her constant rotation, personifies this confusion, reflecting the turbulence of her thoughts and emotions. Her feet and eyes are vivid symbols of that uncertain walk and incessant quest for clarity. However, despite efforts, we do not find consensus, and we are enveloped by sadness and become mere objects of the reality around us.

It is in this context that we represent the mismatch of thoughts, an anguished state that permeates our lives and often prevents us from moving forward. We are trapped in a constant vortex, spinning in circles, unable to find a clear way out. This tumultuous dance of thought confuses us, imprisons us and takes us away from the path that leads to progress and fulfilment.

"Desconcerto do Pensamento" invites us to enter the inner labyrinths of the mind, to confront our doubts and to seek clarity in the midst of chaos. It is an exploration of human vulnerability at the crossroads of thought and a call to find the inner harmony that will allow us to move towards truth, understanding and peace of mind.

Figure 5. “Desconcerto do pensamento”

“Reflexão” (Fig. 6), project by Ana Marques and Daniela Homem.

“It intends to show the way people are in society in contrast to what they really feel. In a first phase of this hologram appears the character reflected in the mirror, made up and charming as if she had returned from a public event. The first moment thus shows the image that the character demonstrates in society, in contrast to the second moment when its image reflects its real state of mental health. At the moment when the viewer is facing, the reflection in the mirror shows that it is quite shaken, with undone make-up and with a casual outfit. When there is a change of video in the mirror, colour is changed to less intense saturation to demonstrate the characters own feeling.”

The "Reflexão" project aims to portray, in a deeply evocative way, the discrepancy between the personas that people display in society and their underlying emotional realities. Through a carefully conceived hologram, the students sought to explore this duality in a visceral way.

In the first stage of this holographic spectacle, the character is reflected in the mirror, boasting a meticulously constructed image, with impeccable make-up and an imposing look, as if she had just arrived from a prominent social occasion. This visual representation captures the mask that the character displays to the world, as opposed to the second stage, in which her true mental health is revealed. As the character stares intently at the viewer, the reflection in the mirror exposes a shaken figure, with faded makeup and casual attire. This visual transformation is accompanied by a subtlety of saturation, in which the colours are attenuated, thus encapsulating the deep feelings that afflict the character.

"Reflexão" seeks to incite a deep reflection about the masks we wear in the social sphere and the anxieties we hide behind them. Students therefore invite viewers to question ephemeral appearances and contemplate the importance of an authentic connection with our emotional world, recognizing that what is shown does not always faithfully reflect what one feels.

Figure 6. “Reflexão”

“Trip” (Fig. 7), Catarina Santos, Dário Marcelo, João Figueiredo and Rafael Pereira.

“We wanted to represent a chaotic reality that involves a subject as he/she metamorphoses from identity to identity, in different psychological states. To get that sense of chaos, we created several contrasts, for example, motion, repetitive (legs), organic (background) and linear (faces). The video is also covered with a “dots and points” texture to enhance the surrealistic side; this filter that resembles the comics in combination with the realistic faces creates a new layer of contrast that activates the feeling of “Uncanny Valley”. Lastly, the faces featuring all the group members blend in succession with each other to create a transition of identities and moods (Neutral, Intrigued, Malevolent and Glad).”

In the "Trip" project, students undertook a daring representation of a chaotic reality, in which an individual metamorphoses between different identities and psychological states. With mastery, they created an atmosphere full of contrasts that underline this feeling of disarray.
Through carefully selected visual elements, such as the repetitive movement of the legs, the organic background and the linear facial expressions, the contrasts come to life. In addition, a “dots and points” texture filter was applied to the video evoking a surreal aesthetic that, combined with the realistic faces, creates a new layer of contrast that evokes the “Uncanny Valley” feeling.

As a final touch, the faces, which portray all the members of the group, merge in a continuous sequence, promoting a fluid transition between identities and moods, which vary between neutral, intrigued, malevolent and happy.
The "Trip" project is an intense and involving immersion in a chaotic world of transformations, where spectators are invited to contemplate the fluidity and complexity of human identity. It is a fascinating journey through the turmoil of emotions and experiences that make up us, challenging us to explore the multiple facets of our own existence.

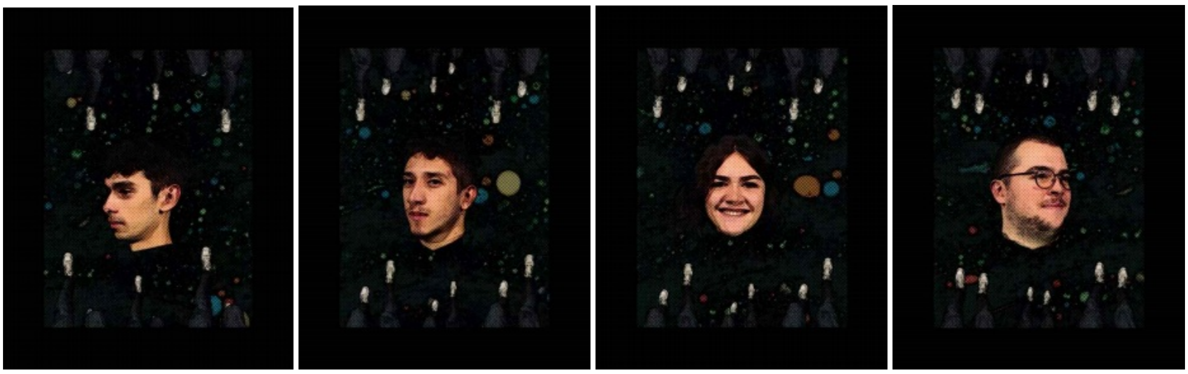

Figure 7. “Trip”

7. CONCLUSION

The convergence of art and new media engenders a vast spectrum of artistic approaches that employ digital technologies, among which the fascinating area of holography stands out. By promoting the materialization of fluid and ethereal images, artistic holography opens horizons for innovative reflections and immersive aesthetic experiences. In Portugal, this form of expression has found space in laboratories and universities, gaining particular relevance in the field of higher artistic education, however, it was at the Coimbra Education School that digital artistic holography was taught for the first time, within the scope of curricular unit of Art and New Media that aimed to provide students with a solid training in digital holography, but also, briefly, in its analogue aspect.

The students were divided into work groups, having developed projects based on the investigation of a theme, in which they rehearsed the conception and production of visual discourse, the incorporation of technology and the evaluation of the experience.

Despite not knowing if the projects would be selected and printed as digital reflection holograms, the thought of the final result in the form of a holographic image and the observer's position in front of it crossed the entire process of creation and production of these projects.

Under the aegis of this enriching curricular unit, students had the opportunity to develop innovative projects, whose objective is to participate in the prestigious international competition integrated in ISDH 2023.

The conceived projects covered themes of deep relevance, from the sublime nature to the fertile childhood imagination, without forgetting the incessant search for love. To give perfect visual quality to the video recordings, the Chroma-Key technique was skilfully employed, with the images subsequently subjected to a meticulous editing process.

The digital holography carried out by the students, in turn, lends renewed vigour to the creative universe, revealing a wide range of expressive possibilities. Through this unique form of artistic expression, it is possible to conceive genuinely unique works of art, capable of surprising and enchanting, thus perpetuating the intimate relationship between technology and aesthetics.

ACKNOWLEDGEMENTS

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My journey from color holography to pulsed portrait, holographic printing and lenticular lens 3D display

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Abstract

Holography[1], a technique of 75-year-old history but still thriving and developing in recent years, has always been a fascinating art and science for three-dimensional (3D) imaging. My journey of practicing holography began as a hobby. In the last 18 years, I have tried several different holography, such as color holography, pulsed portrait, and holographic printing. Obtaining high quality holograms in those needs very different requirements. A brief review on technical aspects is discussed. Finally, lenticular lens 3D video display is also compared with holography.

1. Early experiences of holograms and holography

My first knowledge about holography as a special technology for 3D display was from "A hundred of thousands of questions and answers", a famous set of educational books about science in China, in my childhood. It described "What", "How" and "Why" about holograms and even showed a color photo in the book. Since then, I had been hoping to see a real hologram in a science museum. However, it took 5 years for me to see the hologram for the first time, an embossed hologram[2] sticker on the case of National™ (old brand name of Panasonic™) video cassette in 1988. Later, in the textbook of high school physics, a diagram of how to make hologram by interference was shown but did not explain why 3D image could be reconstructed. In the early 1990s, souvenirs in the shape of round glass showing bright 3D image in direct sunlight, a type of mass-produced holograms of dichromated gelatin[3] in the sandwich of glass, became very popular. I was wondering why "holograms in the books" are different from what I saw.

In April, 1994, more than a decade after reading holography in books, I saw the transmission hologram[4] illuminated with expanded helium-neon (He-Ne) laser[5] beam for the first time when I visited the Chinese Museum of Science and Technology in Beijing. The big hologram had a size of about 1 meter by 1 meter and showed a 3D image of Avalokitesvara (Guanyin Bodhisattva, Goddess of Mercy). The display was installed in the dark area so the image was visible from the big hologram upon illumination of a 2-meter long He-Ne laser tube. It was extremely impressive and was the exact type hologram as shown in textbooks. More surprisingly, several pieces of ultra-realistic reflection holograms of metal tools in the museum caught everyone's eyes. They were broad-spectrum Denisyuk[6] holograms of very high diffraction efficiency. The transmission hologram installation and reflection holograms were removed later and never showed again, as the museum has relocated twice since the 1990s. In the 2010s, a transmission hologram of "Monkey king" illuminated with 532 nm laser and many large-sized reflection color holograms printed in hogels dominate the holographic exhibition in that museum.

Since then, my dream of seeing a hologram became making a hologram. Due to the obstacles of lacking good recording materials and knowledge, it took even longer for me to fulfill the dream.

I purchased a 5 mW He-Ne laser tube of 25 cm length and high-voltage power supply in August, 1994 at the cost of 4.4 months of living expenditure for a college student in China at that time, but never recorded a hologram with it. The tube of randomly polarized laser broke down due to slow gas leaking within a year, while I was searching for Kodak 649-F plates or films, the legendary holographic recording material frequently mentioned in early research papers. The dead laser tube is still kept in a box today, waiting for a piece of historical Kodak 649-F silver halide emulsion, in the form of plate or film, exposed or unexposed, as antiques to recollect the sadness of the old days.

Red keychain lasers of 5 mW diode appeared on the market in 1998 in China. It quickly became a cheap and robust reincarnation of the dead He-Ne laser tube. While lacking holographic recording materials, the toy laser was indeed very good for demonstrations of single-slit diffraction, pinhole diffraction, Thomas Young's experiment (double-slit experiment), Fizeau interferometer, Michelson interferometer, and Poisson spot (Arago spot), etc. It was a tiny tool to review the developing history of wave optics.

My first hologram recording was made with Integraf film kit (www.integraf.com) and a 5 mW 650 nm laser diode in September, 2005. The laser exposure experiments were carried out at night in my apartment in Fayetteville, Arkansas, US, when I was a Ph.D student in Biochemistry. Like traditional film photography, one needs at least several rolls of film to practice the combinations of shutter speeds and lens apertures until good quality photos can be taken. Without a laser power meter, my experiments were completely based on trial and error. I tried several boxes of ultra-fine grain (crystal size less than 10 nm) plates of PFG-03M, PFG-03C and dozens of film sheets of fine grain (crystal size about 60-100 nm) PFG01 and VRP-M until satisfied results of reflection and transmission holograms were made. Meanwhile, contact Denisyuk holograms of 532 nm laser from a 2-3 mW laser pointer recorded with PFG-03C were successful. Not knowing that a low power diode laser such as a 5 mW 650 nm diode is very good for holography because of its good single longitudinal mode (SLM) and free of mode-hoping, I disassembled a powerful 200 mW 650 nm laser diode from a DVD burner, but to find that multi-mode laser can only produce "sliced bread" holograms and the coherence length is merely 1-2 mm! Since then, I have tried 405 nm 20 mW, 445 nm 1 W, 445 nm 80 mW, 650 nm 50 mW, 650 nm 200 mW, 638 nm 185 mW, 638 nm 700mW diodes. But even with good heat dissipation and powered with circuit of constant current, those diodes provide bad coherence length. Generally speaking, high power diodes run in multi-mode and SLM can only be obtained by carefully adjusting the working current and temperature. However, the maximum output of SLM in those high-power diodes would be less than 20 mW.

2. Color holography[7]

In 2013, my holographic laboratory was equipped with a long tube (1.2 m) 40 mW He-Ne laser and a diode-pumped solid state (DPSS) 200 mW 532 nm laser for testing 2-color Denisyuk holograms. A detailed report of making color holograms in a home laboratory had been reported in ISDH 2015 in St. Petersburgh, Russia. In summary, a mathematical method of calculating exposure time for balanced color of 2 or 3 wavelength lasers considering low intensity reciprocity failure (LIRF)[8] for ultra-fine grain silver halide emulsion had been proposed. It is not necessary to use a panchromatic silver halide emulsion to make color holograms. In fact, the intrinsic sensitivity on green or blue spectrum of red-sensitive plates can be utilized to make color holograms, but several parameters of sensitivity on green or blue spectrum need to be measured in order to calculate accurate exposure times for balanced colors.

While doing holography experiments, I quickly ran out of expensive commercial holographic recording materials. By reading early research papers on holography and Lippmann photography, I began experiments of making silver halide emulsions in 2014. With a background of chemistry, I successfully made ultra-fine grain holographic plates of high sensitivity to red and green spectra.

In the early days of my laboratory, I had to use the same laser for many purposes, such as making Denisyuk hologram, transmission hologram H1 and recording of a transferring reflection hologram of H2. It is time-consuming when switching laser for different usages. As more experiments of holography were carried out, more lasers of SLM were needed. The external cavity diode laser (ECDL)[9] would be a good choice for SLM lasers for holography at a low cost. The diode itself is usually cheaper than the optical grating for laser assembly. Extensive tests of laser diodes for ECDL had been reported by excellent work by W's Laser-Projects (http://hololaser.kwaoo.me/). I made an ECDL with Opnext HL63603TG diode of 638 nm 120 mW with a blazed grating of 1800 groves/mm. With a constant-current power supply and temperature control for the Peltier cooler, ECDL could output very good SLM at 80mW or more. After fine tuning of the grating angle and monitoring fringes with a simple Fizeau interferometer, it recorded very good Denisyuk holograms.

PL-530 [10], an optically pumped semiconductor laser (OPSL) used as the green light source in the early type of Microvision Pico Projector (later types use 520 nm diode), has been well-known for its long coherence length, and has been widely used by hobby holographers. It is worth mentioning making 2-color holograms when used with a red ECDL. I received 2 pieces of the tiny but superb laser for its SLM property from my friend Jiri Sonsky in Czech Republic in 2020. It outputs about 1/3 power of my expensive 200 mW 532 nm DPSS but is capable of the same application for color holography.

Figure 1. Two-color (532 nm and 633 nm recording) holograms made in August, 2013

Left: hologram of cartoon statues of Chinese gods of fortunes

Right: hologram of cartoon statues of Guan Yu, Liu Bei, Zhang Fei (3 famous Chinese generals in the three-kingdom period, AD 220-280)

Figure 2. Left: two-color hologram (lower diffraction efficiency due to incorrect exposure) of cartoon statues of the Chinese gods of longevity and mascot.
Right: monochromatic (633 nm) hologram of a statue of a Chinese dragon

3. Pulsed holography

A serious holographer should never neglect the ruby laser[11], the first laser invented in 1960. Being a textbook example, the ruby laser was taught in physics courses from high school to college. Nevertheless, this legendary laser is far beyond the imagination of any student in a classroom, as ruby in Chinese means “red gem stone”. Students won’t know the detailed atomic percentage of Cr^{3+} in the corundum of the synthetic rod and other parameters unless doing literature search, a difficult step before the Internet. Thus, the formidable “gem” laser was out of consideration by many holographers. In fact, the cost of the ruby rod is largely determined by optical homogeneity and high precision polishing rather than the “gem” material. It is a good starting point of do-it-yourself (DIY) project of pulsed lasers for holography. Usually, the difficulties lie in obtaining a ruby laser rod and making the power supply for a flash lamp with a high-voltage trigger. Due to lower efficiency than that of the current solid pulsed lasers, ruby laser rods went out of production for a long time. But sometimes these items can be found on eBay. With the help of my friend Jiri Sonsky in Czech Republic, who DIYed the power supply with a trigger for pumping a flash lamp, I began my pulsed holography at the end of 2018. The ruby rod is the size of 6 mm * 120 mm (diameter * length) and made in the Soviet Union. Mirrors of the output coupler (OC) and high reflectivity (HR) are quartz glass and HR from He-Ne laser. The assembly of water cooling and ceramic reflector are parts of a 1064 nm welding laser. Optical alignment of the system was done with the help of the 5 mW diode laser. A ruby laser of simple optical cavity (Fabry–Pérot cavity) without an etalon or a dye cuvette as Q-switch absorber can produce a single pulse of millisecond duration in multi-mode at 694 nm with each pumping. It is good enough for making a contact Denisyuk hologram of coins or very shallow objects. Multiple-flash exposure is required when using 633 nm ultra-fine grain emulsion. When a cuvette of diluted cryptocyanine[12] solution in ethanol is used as a saturable absorber for the Q-switch in the optical cavity, the ruby laser outputs a single pulse of nanoseconds with one pumping. More importantly, the absorption of cryptocyanine at 694nm is inhomogeneously broadened and the spectral hole burning effect during light bleaching renders cryptocyanine as a narrow-wavelength filter. A ruby laser with cryptocyanine Q-switch generates a de facto SLM beam and the coherence length is very good for holography. However, pulses of nanosecond level duration result in another problem, extremely low sensitivity of silver halide emulsion when exposed to very short pulse(s), i.e., high intensity reciprocity failure (HIRF)[13].

I kept a dozen sheets of Fuji panchromatic holographic film purchased in 2010 in the US. It is silver halide emulsion of fine-grain crystal size and has a broad-spectrum sensitivity of 473 nm, 532 nm, and 694 nm. Unfortunately, this nice and affordable film went out of production for a long time. I made several transmission holograms with Q-switched pulsed ruby laser and Fuji panchromatic holographic film, then quickly moved to the next step.

The ruby laser project is a good starting point for learning high-voltage trigger and electronics for flashtube pumping, knowledge that is also required in other flashtube-pumped lasers. Once you are confident and comfortable with high-voltage electronics, it is a good time to try Nd: phosphate glass rod, Nd:YAG rod, and laser with amplifier(s). Mirrors of OC and HR for 1064nm are widely available on the market in the laser industry and there are many options for reflectivity of OC. Like ruby laser rods, eBay is the right place to find Nd: phosphate glass rods while Nd:YAG rods are widely available in the laser industry. Nd:phosphate glass rods are in relatively large size and cheaper than other types of laser rods. But Nd:phosphate glass rod emits at 1060 nm peak and has a much broader spectrum of lasing than Nd:YAG rod. I tested Nd:phosphate glass rod for lasing but did not use it for holography.

High power pulsed lasers of 1064 nm and doubled frequency 532 nm in industrial and commercial applications have made them cheaper and cheaper. One of the cases is the laser for removing tattoos. Upon flashtube pumping, a Nd:YAG rod (5 mm*85 mm) in a simple optical cavity of short distance outputs pulses of about 8-10 nano-second pulse duration with a Q-switch of Cr^{4+}:YAG crystal. High energy (up to 2 J per pulse) and very short pulse duration made these lasers extremely dangerous. Air can be ionized in the focusing center of the laser beam, generating a loud sound and flashing white. The potassium titanyl phosphate (KTP) crystal in the laser head doubles the frequency to output 532 nm beam. When applied for making Denisyuk holograms, exposure of multiple pulses at 300 mJ energy per pulse for the ultra-fine grain silver halide emulsion showed image of about 1 cm depth of the contact object. Single-pulse exposure at the same pulse energy for the fine grain transmission hologram demonstrated about 4 to 5 cm coherence length. Without etalon, the wavelength of each pulse varies slightly and multiple-pulse exposure results in less coherence length than single-pulse exposure. The coherence length of such a laser decreases dramatically as pulse energy increases.

A similar situation happens as in high-power diode lasers: outputs of high energy or power sacrifice the coherence length and render the laser useless for holography. So, modifying such a laser of Fabry–Pérot cavity to a ring-shaped traveling-wave resonator laser is of crucial importance. By adding three 45-degree dielectric mirrors and a 45-degree OC, coherence length increases dramatically. But pulse energy also decreases compared to simple cavity resonator with the same pumping energy. When pumped with maximum allowed energy (pumping energy for 2 J output of 1064 nm in the previous simple optical cavity), insufficient coherence length is visible in transmission holograms. In order to get a pulsed laser suit for high quality portrait holography, I made a laser composed of a seeding resonator of SLM traveling-wave cavity with 2 stages of amplifiers. An etalon was installed in the seeding resonator to make sure SLM pulses were amplified in the following stages. Pumping lamps for seeding resonator and two stages of amplifiers must be synchronized.

In long rod Nd:YAG laser or Nd:YAG laser with multi-stage amplifiers, a serious problem exists as the amplification of spontaneous emission (ASE) causing significant energy waste. The ASE outputs as a millisecond duration pulse, much longer than the Q-switched nanosecond pulse from the seeding resonator. A large amount of energy stored in upper-level dissipates as unwanted non-laser light before the Q-switched pulse arrives in the amplifier(s). To overcome the problem, short (85 mm) Nd:YAG rods are used in the seeding resonator and first-stage amplifier, and two Cr^{4+}:YAG crystals are inserted between two consecutive Nd:YAG rods in the system.

Once the SLM pulsed laser has been setup and runs smoothly, pulsed holograms can be made with a similar optical setup in still-object holography. One has to be careful about the optical path difference and the beam ratio. The beam-splitter should be used in the path of an expanded beam and never put it in direct output of a pulsed laser. A wireless switch of trigger for the pulsed laser provides convenience and safety.

My first pulsed portrait hologram was recorded on August 6, 2019, with a traveling-wave laser of single stage amplifier, as a transmission hologram with VRP-M film of Slavich. A much better pulsed portrait hologram was recorded on December 18, 2019, using a laser composed of a SLM traveling-wave seeding resonator with 2 stages of amplifiers. Figures 3 and 4 show the photos of the holograms.

Precautions of safety:

My niece once asked me at the age of 7, when visiting my laboratory: “Why is all of your stuff so dangerous? Either corrosive or high-voltage.” I was quite amused by her concise summary and failed to give her a short answer suitable for a child. We are indulging in the beauty of holography but we are dealing with chemicals, high-intensity light, and high-voltages to get a 3D rendering of the world, so be careful and always remember that safety is the first priority.

Pulsed holography involves very high peak power (up to the scale of a billion watts), high voltage for flash lamp triggering and a large amount of energy stored in a bank of big-sized capacitors for laser pumping, so check everything at least 3 times. Make a checking list for safety.

Figure 3. My pulsed holographic portrait, viewed from different positions

Figure 4. Pulsed hologram of my hands

4. Holographic printing[14, 15,16]

Holographic printing based on hogels combines the advantage of high fidelity of holographic imaging and the versatility of computer-generated imagery (CGI). A simple description of the fancy technique is to replace the real objects of holography with 2D images displayed on a transparent LCD screen (with a diffusor), and to make a huge number of element holograms on recording plate, while the corresponding image for each hogel is correctly displayed on LCD according to the position of the hogel for laser exposure. Today's availability of LCDs, stepper motors and movement controlling devices such as C51 or Arduino single-board microcontroller (SBM) or Raspberry Pi single board computer (SBC) have made it possible for holography enthusiasts to do experiments. If you are an experienced analog holographer and have moderate knowledge of programing, electronics and computer graphics, it is the right time to try holographic printing. To make things easier, the movement part of the system could be modified from many open-source 3D printers, or use mechanical system for similar applications.

A key unit of the system is the controller to synchronize the movement of the holographic plate, correct display of LCD images and state of shutter of the laser beam for exposure of individual hogel. If non-pulsed lasers are used, stabilization time after each step of hogel movement must be waited before exposure of each hogel.

Details of holographic printing about image generating for hogels, programing the movement of the recording stage, and output the images to LCD via a PC or a Raspberry Pi SOC are far beyond the space limit of a conference paper. Figure 5 and Figure 6 showed monochromatic (532 nm) recording of holographic printings I made during the pandemic of Covid-19 in 2021.

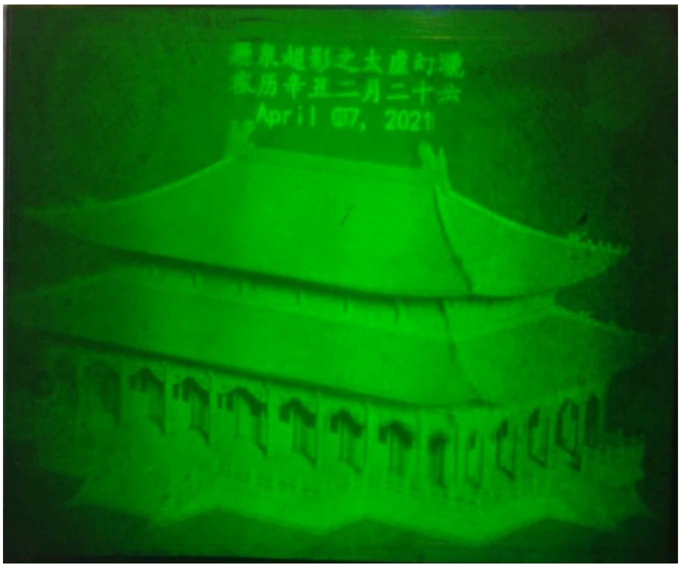

Figure 5. 532 nm holographic printing of a computer-generated model of an "Ancient Chinese palace”

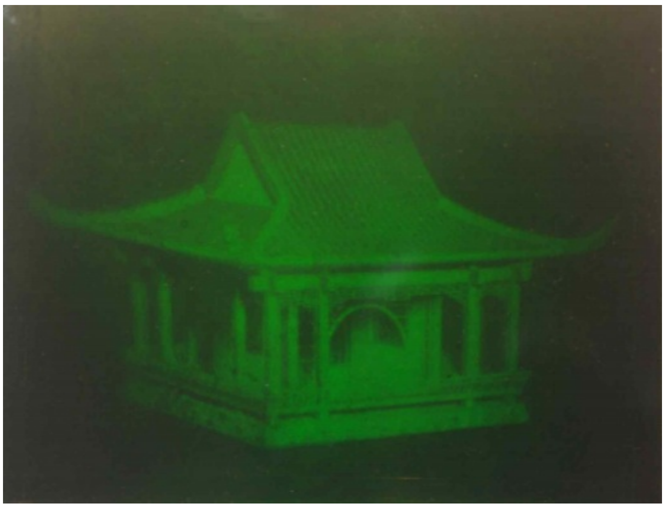

Figure 6. 532 nm holographic printing of a computer-generated model of a “Chinese water pavilion”

5. Lenticular lens 3D display and naked-eye horizontal parallax 3D video

While holography provides the most realistic means for rendering the world, we expect even more about replication of reality: time sequences of 3D images, or 3D video. Although 3D movies of stereoscopic-glasses appeared in the late 1980s in China, large-size holograms are still rare today. Naked-eye 3D movies of full parallax are our final dream in reproducing reality. This luxury dream has to be scrutinized mathematically first before we can put efforts and money into it. Time sequences of true 3D images of full parallax mean huge amounts of data. How can we record, store, and transfer a huge amount of data? Do we really need all of the data? Holographic movies for consumer markets are an impractical dream unless we can record holograms quickly and at low cost.

Lenticular lens 3D display, an old technique as sister of integral photography[17] which was proposed by Gabriel Lippmann in 1908, still deserves reexamination today. Unlike his another invention of Lippmann color photography[18] which is based on interference of light, integral photography is based on simple geometric optics. Thus, the necessity of a great amount of data used in holographic 3D rendering can be significantly relieved. Our visual perceptions of the world do not count on every photon coming into our eyes, so it is not necessary to render the world as accurate as in holography.

When dealing with image generation for integral 3D display, one would find that the same mathematical principle governs the light propagation in integral photography and holographic printing. In fact, integral photography and holographic printing are just two different methods to simulate the same physical phenomena: light propagation from 3D objects.

I began experiments of lenticular lens 3D display in 2021. Although image quality is far inferior to holograms, the advantages are simple and quick 3D vision generation in color. It takes a long time to generate a hologram by holographic printing but “recording” and “reconstruction” of lenticular lens 3D vision is as easy as output an image on LCD. Simplicity of the process made it possible to render time sequences of 3D vision in color, i.e., naked-eye horizontal parallax 3D video in color. A pocket display device of 12-degree horizontal parallax and about 10-cm z-axis depth of clear vision has been made in my laboratory in May, 2022.

Figure 7. Lenticular lens 3D display device showing a naked-eye horizontal parallax 3D video “Rotating Chinese water pavilion” in color

Figure 8. Lenticular lens 3D display device showing a naked-eye horizontal parallax 3D still image of “Ancient Chinese palace” in color

As in the early ages of photography, experiments of holography are heavily burdened by financial budgets, especially for self-funded individuals. The equipment of SLM lasers and optical items is expensive, not to speak of silver halide recording materials, which have to be largely consumed in order to overcome the pricey learning curve. Unless you were born rich and can afford all those, or working in a state-funded laboratory at university, DIY is a possible way not only for financial reasons but also for learning and having great fun. I hope my personal experiences can help those new holographers. Buy what you can afford, then try DIY, to build or modify things for your needs. DIY lasers, DIY recording materials, DIY programs for image processing, DIY printers for hogel-printing, and you will learn and grow.

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The contribution by nils abramson to the field of holography

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ABSTRACT

Nils Abramson (1931 - 2019) was one of the true pioneers of holography. Shortly after lasers were made available in the 1960s, he started research on how they could be used in engineering. With a background as a mechanical engineer, much of this work naturally came to deal with holographic and other types of interferometry, but his work has also contributed to the general understanding of holography. Examples of his work includes holographic interferometry, sandwich holography, the Holodiagram, Light-in-flight recording by holography and the relation between holography and relativity. This presentation gives a biographic description of the professional life of Nils Abramson and short introductions to and explanation of his results.

Keywords: holography, interferometry, relativity

1. INTRODUCTION

Nils Hugo Leopold Abramson was born in Stockholm in 1931. His father, Hugo Abramson, was a renown engineer, at the time employed at the Swedish industrial gas company AGA AB. The father later became head of development at CE Johansson, a metrology company based in Eskilstuna, Sweden. His inventions include a portable recoilless anti-tank weapon, which, in updated versions, is still in production today. He also developed the Mikrokator, a highly sensitive and accurate mechanical length indicator.

Nils Abramson received his Master of Engineering from Royal Institute of Technology (KTH) in Stockholm in 1960. He remained at KTH for most of his professional life. When the laser became available in the 1960s he soon realized its potential for mesurements and started using it in his research. He received a licenciate degree from the Department of Machine Tools, KTH in 1965 [1], and Doctor of Engineering from the Department of Production Engineering in 1974.[2] He was appoited docent (assistant professor) in 1974 and professor in 1981.

Abramson received several awards including the Arnberg prize by the Royal Swedish Academy of Sciences in 1980, the KTH Great Prize by the Royal Institute of Technology in 1985, the Gold Medal for Pioneering Work on Laser Metrology by the Royal Swedish Academy of Engineering Sciences in 1995 and an honorary Doctor in Physics degree from KTH in 1996.

He retired in 1996 but that did not make much difference to his daily activity. He still came to office almost every day and kept on thinking, writing and publishing papers. At the time of his death in 2019 he was just finishing a last paper.

Nils Abramson published two books and over 160 international papers.

2. THE EARLY YEARS

During the years 1955 and 1956 Abramson was working at the scientific instrument makers Thomas Mercer Ltd. in England. After graduating from KTH in 1960 he started working at the Department of Machine Tools. After finishing his licenciate thesis he moved to the Department of Production Engineering. Abramson was from early on interested in applying interferometry for mechanical measurements and at that time lasers started to become available, and he then decided to spend his time developing the engineering uses of lasers. With the support of professor Bertil Colding, he started a number of research programs in the field.

2.1 The Interferoscope

As an example of Abramson's inventions made during the 1960s it is worth to mention the Interferoscope[3], which first was suggested in 1967. The Interferoscope is a Fizeau type interferometer in which the sensitivity can be changed by a rotating prism so that the object under test is illuminated at near-grazing incidence (Figures 1 and 2). Achromatic fringes will be produced if white-light illumination is used. Thanks to the variable sensitivity, the Interferocope can be used for measuring the height of uneven surfaces, which is not possible with standard Fizeau interferometers. The concept has since been developed further by several workers.[4]

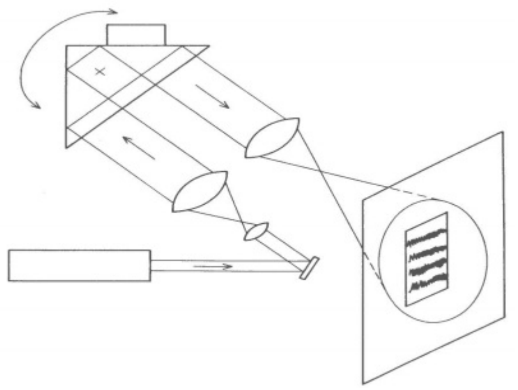

Figure 1: The principle of the Interferoscope.

Figure 2: Interferoscope prototype

2.2 Moiré techniques

Abramson did not like mathematical explanations very much. He stated: "Holographic interferometry is not complicated in itself, it is the mathematical explanations that are complicated".[5] Instead he tried to find graphical interpretations and explananitions. He early identified the close analogy between interferometry and moiré patterns and used moiré pictures in order to understand the phenomena and convey his ideas.[6] The concept was particularily useful in teaching.[7] He managed to find the moiré equivalent in most of his work in interferometry and holography and even extended it to explain his thoughts in fundamental optics and physics. He also early suggested the use of the moiré effect directly for measurements, bypassing the step of making a hologram.[8]

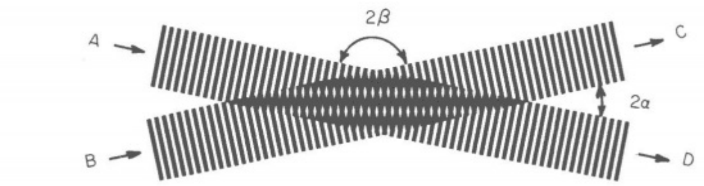

Figure 3: The moiré analogy. The two striped patterns A and B represent coherent light beams propagating in the direction of the arrows. Where they cross each other, new stripes, moiré fringes, are formed. These are equivalent to the interference fringes in optics.

2.3 Sandwich holography

The common method in holographic interferometry is to make two exposures on the same plate. If the object has moved or deformed between the two exposures, interference fringes, giving information about this movement, can be seen in the hologram. These interference fringes are stuck in the image and cannot be adjusted later. In sandwich holography, introduced by Abramson in 1973[9], the two exposures are made on different plates which are sandwich later for evaluation. The technique of making the holograms on different plates had actually been suggested earlier[10, 11], but Abramson developed the idea further. By manipulating the two holograms when viewing, the interference fringes can be adjusted so that more information can be extracted, such as the removal of rigid motion of the object or separation between inwards and outwards deformation. Sandwich holography was expected to have important uses in the industry so a number of project were performed at KTH during the 1970s.[12]

3. THE HOLODIAGRAM

The Holodiagram [13-18] is a seemingly simple idea that Abramson managed to develop into a very powerful visualisation tool. This tool followed him in his career and he used it for visualisation in such diverse fields as holographic interferometry, cosmology, relativity theory and geometry.

3.1 As a tool for display holographers

In one of its more direct incarnations the Holodiagram can be used to plan the setup when making holograms. In this application the diagram can be constructed in the following way (Figure 4): Let *A* be the point from which a spherical divergent laser beam originate, and *B* a point on the recording holographic plate. The distance travelled for a light beam from *A* to *B* is constant on an ellips with its focal points in *A* and *B*. When making a hologram with the use of a laser with a limited coherence length, the path length travelled by the object and the reference beam need to be the same, or, at least it should not differ more than the coherence length. If the diagram in Figure 4 is drawn so that the distance between each ellips represents a light path difference of one coherence length of the laser. In the figure every second of those distances are colored black for clarity. If the holographer places her object so that it fits entirely between two of these ellipes she can be sure that the whole object will be within the coherence length of the laser and hence has a good change of being reproduced in a bright image. In the same way, a mirror directing the reference beam from the light source at *A* and the photographic plate at *B* should be placed inbetween the same ellipses as the object.

3.2 As a tool for analysing holograms and holographic interferometry

Using the moiré analogy it is possible to draw a diagram such as that in Figure 5. In this diagram a set of ellipses similar to the ones in Figure 4 can be identified. A set of hyperbolas can also be seen. If the points *A* and *B* now represent two coherent spherical light sources radiating outwards, the hyperbolas represent the stationary interference fringes produced between the two light sources. In three dimensions these are hyperboloids with rotational symmetry. The intersection of these hyperbolids and a plate inserted anywhere in space will give the interference pattern that would be recorded in a hologram of the two light sources. In this case the corresponding ellipsoids will not be stationary, but instead move outwards at high speed. A hologram made from this interference pattern will produce a virtual image on point *B* when illuminated with the diverging light from point *A*.

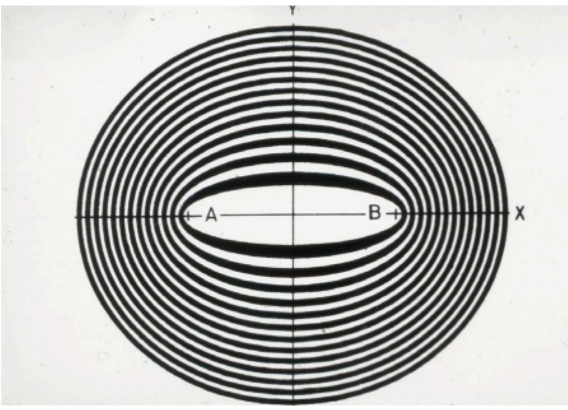

Figure 4: The set of ellipses in the Holodiagram are useful in planning the holographic setup.

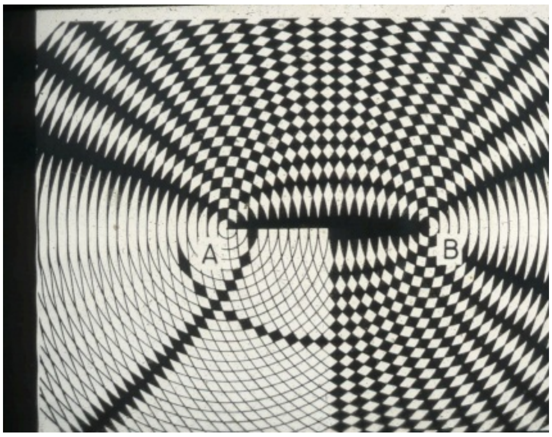

Figure 5: A Holodiagram drawn using the moiré analogy. The points A and be can be seen to be the focal points of a set of hyperbolas and a set of ellipses.

If light around e.g. point *B* instead moves inwards, so that we have one divergent and one convergent lightfield, the ellipsoids will be stationary in space while the hyperboloids will move. In this case the point *B* can be seen as the point of observation, i.e. the position of the eye when viewing a hologram. A hologram made from these ellipsoids will produce a real image of point *A* at *B* when illuminated with the diverging light from point *A*.

To consider *B* as the point of observation proved to be very useful when evaluating holographic interferometry. The ellipses now represent the locations where the distance the light has travelled from the source is constant. In holographic interferometry a dark fringe will occur when this distance has changed half a wavelength compared to the reference exposure. The dark fringes will be repeated every time the distance change another wavelength. So the ellipses in the holo-diagram can be used for evaluation of the fringes in holographic interferometry.

4. LIGHT-IN-FLIGHT RECORDING BY HOLOGRAPHY

The technique of studying laser pulses by the use of holography seems to first have been proposed by Staselko et al.[19] in 1969. Abramson, appearently unaware of their work, briefly mentioned, in his paper from 1972 [18], that holograms could use a short laser pulse as a shutter for gated viewing experiments. Some years later he published the technique he named "light-in-flight recording by holography" (LIF) [20-23]. The principle is shown in Figure 6. Light from the laser *L* is illuminating the object *O*, which in this case is just a flat screen. Reference light is directed by mirrors *E* and *D* towards the holographic recording plate *B*. The reference light is falling at the plate at a steep angle. If the laser light is in the form of a short pulse, much shorter than the width of the holographic plate, the whole plate will not be covered at once, but the pulse will travel across it at the speed of light. Since the object and references light both need to be present to form a hologram, the reference pulse will act like a curtain shutter sweeping along the recording plate. In the finished hologram, illuminated with a continuous laser, the viewer will see the first illuminated part of the object when looking through the left part of the hologram and the last illuminated part when looking through the right part of the hologram. When moving the eye between these two points the viewer can see a continuous movie showing the light pulse passing over the object. A LIF hologram can be made using a single laser pulse or a pulse train from a mode-locked laser. It will also work with a continuous laser with a short coherence length. Since interference between the object and reference light only can occur if their path lengths do not differ more than the coherence length of the laser, short coherence will, in this case. work in a similar way as a short pulse. In many respects LIF is similar to the now more common technique Optical Coherence Tomography (OCT).

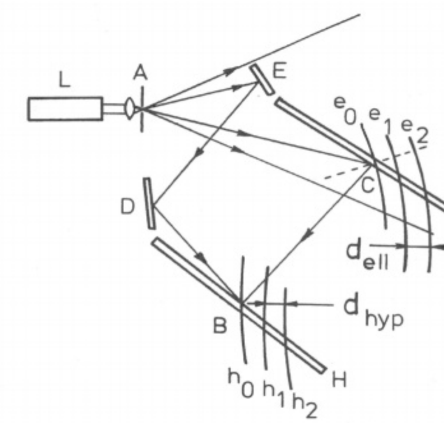

Figure 6: A setup for making a LIF hologram. The recording plate H is illuminating with a short pulse from mirrors E and D. The object is at O.

4.1 Applications of light-in-flight recording by holography

LIF was naturally first used for visualising light propagation, e.g. reflection in mirrors and focussing in lenses.[20, 21]

Abramson also early pointed out how it can be used for acquiring the three-dimensional shape of objects with the use of a very short laser pulse. The first example is shown in Figure 7. [21] A pulse of light passing the object from its front to its back is recorded in the LIF hologram. The light is spread out so it resembles a sheet of light. In the finished hologram this sheet of light is seen passing across the object when the viewer is moving, e.g. left to right. Each position of the viewer represents a moment in time and hence a depth position on the object. The images obtained this way can be recorded two-dimensionally and combined to create a digital three-dimensional model of the object.[24, 25]

Abramson also applied LIF for the testing of optical fibres and imaging of objects embedded in scattering media.[26, 27]

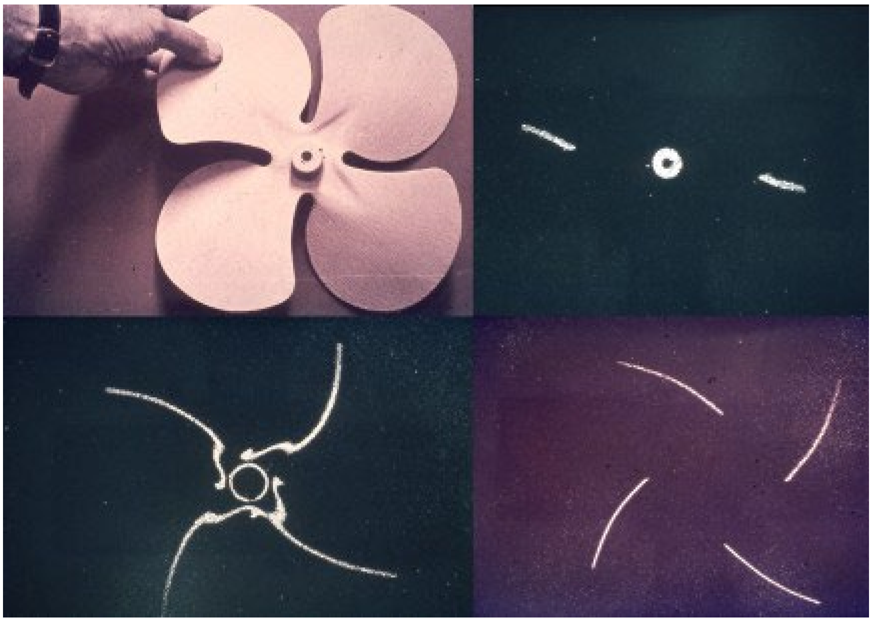

Figure 7: The propeller (top left) is recorded in a LIF hologram. In the hologram a thin sheet of light can be seen intersecting the propeller at different depths. The images can be used to construct a three-dimensional digital model of the propeller.

5. HOLOGRAPHY AND RELATIVITY

5.1 The holodiagram as a tool for visualising Einstein's special theory of relativity

The analysis of LIF made Abramson realise that relativistic effects came into play [23], and also that the holodiagram could be a useful tool for visualising relativistic phenomena.[28] His interest in the theory of relativity actually started much earlier. He used to tell about when his father and he went out to measure the speed of light, using a length measuring instrument called "the Geodimeter"[29], with the purpose to prove or disprove the theory.

Although the application to relativity is not as much a contribution to the field of holography as a contribution to the field of relativity by holography, it can be worth to mention here since it occupied much of Abramson's time the last decades. Using only the graphic constructions of the holodiagram he managed to derive the common phenomena in special relativity, such as time dilation, object distortion (Lorentz contraction) and the Doppler shift. All with a minimum use of mathematics.

Abramson last paper "Asymmetric special theory of relativity" was published in 2018.[30] At the time of his passing a new manuscript was close to completion. That manuscript has not yet been published.

It was also shown that the analogy between holography and relativity could work in the opposite way. The Minkowski light cones was originally devised for visualising relativistic phenomena. Abramson showed how they also could be used to derive the holodiagram used in holography and relativity.[31]

6. FUNDAMENTAL OPTICS AND GEOMETRY

Abramson's study of the holodiagram led to other fundamental ideas in optics and geometry; for example modification of Fermat's principle[32] and how to improve optical resolution.[33]

He also suspected that a section through a rotational ellipsoid by a plane would always look circular when viewed from one of the focal points of the ellipsoid. This seems to be a previously unknown theorem in geometry and it was later proved with the help of mathematicians.[34]

7. TEACHING

In the 1960s, when the laser was a new tool, Abramson gave many lectures to the Swedish industry with the purpose to spread the knowledge of lasers and optical measurement techniques.

He was an appreciated lecturer in metrology for the students at the Royal Institute of Technology (KTH). He often used simple and interesting experiments to demonstrate different phenomena and techniques, and his presentations were graphically very effective. After his (official) retirement he more seldom gave lectures to students.

Abramson gave many lectures at universities around the world. For many years he lectured every summer at the Holography Workshops in Lake Forest, USA, arranged by Professor Tung Jeong.

8. COMMERCIAL VENTURES

In the 1960s Abramson started the research group Lasergruppen (The Laser Group) at KTH together with some colleagues. Lasergruppen developed laser-based measurement techniques and took measurement commission from the industry. Later he also founded Holovision AB together with, amongst others, Hans Bjelkhagen and Per Skande, with support from the company behind the Stockholm newpaper Dagens Nyheter. The purpose of Holovision AB was to develop and sell display holograms. Eventually Lasergruppen and Holovision was merged to Lasergruppen Holovision AB. The company still exists today under the name Holovision AB.

He also founded the company Laserlabbet i Linköping, Sweden, together with Eva Jönsson. Laserlabbet developed injection-molded holograms.

9. BOOKS

Abramson authored two books: "The making and evaluation of holograms" published in 1981[35], and "Light-in-flight or the holodiagram" published in 1996.[36] Both are largely based on his own work and provide a much better and more comprehensive account for his contributions than this short presentation can do.

Figure 8: Tung Jeong and Nils Abramson taking a break from windsurfing.

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Early holography in sweden

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Abstract

Research on holography started in the mid-1960s at the Royal Institute of Technology (RIT) in Stockholm, Sweden. It took place both at the Institute for Optical Research under Eric Ingelstam and at the Production Engineering Department under Nils Abramson. Ingelstam's Institute attracted international researchers like Klaus Biedermann from West Germany and Karl Stetson from the USA. The author Hans Bjelkhagen, one of Abramson's students, finished his Civil Engineering exam in 1969 and started to work on holography, both on hologram interferometry applications and display holography. The department got a pulsed ruby laser in 1971 with Bjelkhagen responsible for it. Also in 1971, when Dennis Gabor got the Physics Nobel Prize in Stockholm, the interest in holography increased dramatically. At that time, it was easy to get funding for research projects on holography. The well-known artist Carl Fredrik Reuterswärd got interested in lasers and holography and cooperated with RIT to record art holograms. In 1974, a hologram of the Swedish Royal Coronation Crown from 1561 was on display at the Stamp Exhibition STOCKHOLMIA'74. The hologram was a main attraction at the show. The First International Hologram exhibition was arranged in Stockholm by the New York Museum of Holography in Stockholm 1976. Both these exhibitions attracted many visitors and people in general became aware of holography. The company Lasergruppen Holovision AB started operation in Stockholm with the focus on display holography. Covered here are the activities in holography between mid-1960s and end of 1970.

1. Introduction

Research on holography started in the mid-1960s at the Royal Institute of Technology (RIT) in Stockholm, Sweden. It took place both at the *Institute for Optical Research* under *Eric Ingelstam* and at the *Production Engineering Department* under *Nils Abramson*. In 1971, when Dennis Gabor got the Physics Nobel Prize in Stockholm, the interest in holography increased dramatically. It was easy to get funding for research projects on holography. Work on holography in Sweden continued not only in Stockholm but also at other Swedish universities and industries.

Most of the early work was in hologram interferometry for measurements of deformations and vibrations. Some interesting early work in this field is covered. Since RIT got a double-pulsed ruby laser already in 1971, which made it possible to perform many types of dynamic measurements. However, since this conference is focused on display holography, mainly early art and display holograms will be described in the following.

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Figure. 1. Gabor gets the Prize from the Swedish King

Figure. 2. Gabor next to his transmission hologram

Dennis Gabor got the Physics Nobel Prize in December 1971. At the ceremony Gabor received the Prize from the Swedish King Gustav VI Adolf (Fig. 1). On December 11, Gabor gave the Nobel Lecture: *HOLOGRAPHY, 1948-1971* at Royal Institute of Technology. During the event, the 50 by 60 cm transmission hologram of Gabor at his disk was on display (Fig 2). It was recorded by McDonnell Douglas Electronics Company, USA, and was donated to the Institute for Optical Research It was illuminated with a mercury-arc lamp with a yellow interference filter.

The First International Hologram Exhibition: *Holografi – Det 3-Dimensioella Mediet* was arranged in Stockholm at the Culture Center. It was installed by *Posy Jackson* and *Jody Burns* of the New York Museum of Holography from where most of the holograms came. Sven Lidbeck of the Swedish AVC company sponsored the exhibition. It took place between March 12 and 28, 1976. The exhibition was located at the upper level of the Center since it was not expected to attract too many people. However, as a matter of fact, no other exhibition has had so many visitors as the hologram exhibition. More than sixty thousand people came to look at the holograms during the two weeks it was open.

Both these events were important for holography and resulted in that it was easy to get funding in Sweden for research projects on holography. It triggered interest in holography at both universities and industries. For example, *Sven-Göran Pettersson* established a holography laboratory at the Physics Department at Lund University in the south of Sweden. He has devoted a lot of time since the early 1970s and over many decades in both teaching holography and on advanced holographic research projects.

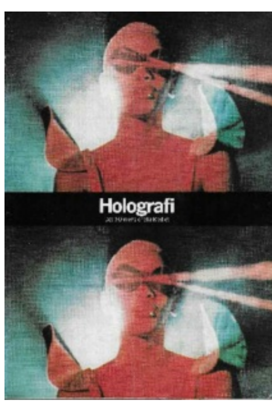

Figure. 3. Exhibition Catalog

Figure. 4. Posy Jackson, Sven Lidbeck and Jody Burns,
Svenska Dagbladet – March19, 1976

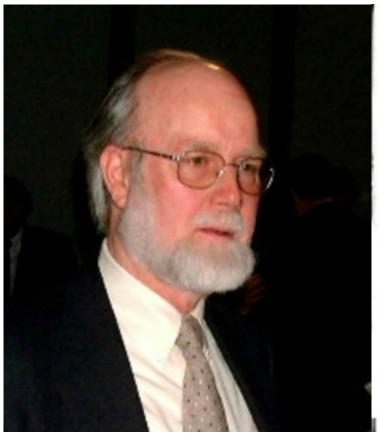

Fig. 4. Karl Stetson

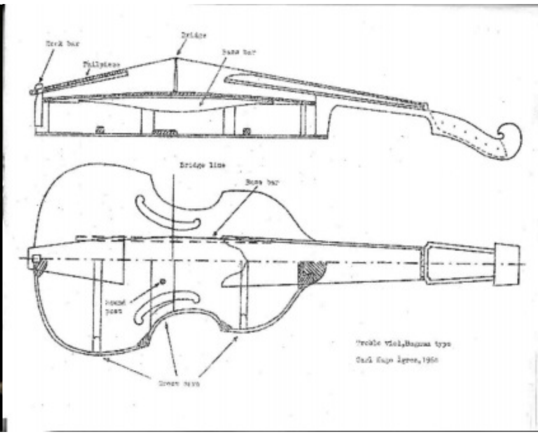

Fig. 5. Magnum treble viol

Fig. 6. Hologram, 503 Hz

2. Institute for Optical Research

The first activities in holography in Sweden started at the *Institute for Optical Research*, under *Erik Ingelstam*. *Klaus Biedermann*, who had experience in holography, arrived from Germany in early 1967. He was familiar with holography and had knowledge about recording materials. He introduced the early Agfa holographic plates to the institute. In September 1967, *Karl Stetson*, (Fig. 4), from USA was invited by Erik Ingelstam to come to the institute where he could work on his doctorate. Stetson arranged a holography lab and was able recording high quality holograms. In the USA, Stetson together with Powell, had introduced the time-average hologram interferometry method for recording vibrations [1-2]. He had also been formulating an analytic approach to holographic interferometry and fringe localization, which also *Sten Walles* at the Institute was working on. They agreed to divide the topic; Walles worked on double-exposure holography and Stetson on holographic vibration studies. In August 1968, Stetson was joined by *Nils-Erik Molin* to work together on holography. He had recorded some display holograms which became very useful for visitors. Stetson together with Klaus Biedermann published a paper on the influence of development time on hologram characteristics. [3] The three of them formed a very effective holography team. Stetson was invited to give a paper at the *Engineering Uses of Holography* conference which was organized in 1968 at the University of Strathclyde in Glasgow, Scotland. [4]

Back in Stockholm, Stetson was asked by *Carl-Hugo Ågren* if it was possible to use holography to measure vibrations on string instruments. Stetson agreed that it could be possible [5]. A treble viol (Fig. 5) was brought to the laboratory. Together they recorded many time-average vibration holograms of the viol at different resonance frequencies [6]. The one at 503 Hz is shown in Fig. 6. Later, at an Acoustical Society of America conference in the USA, Stetson met with John Huber from Martin Guitars. He asked if it was possible to do similar work on guitars. The guitar maker George Bolin in Stockholm provided a guitar mounted on a stand for the recordings. Different vibrations modes were recorded [7]. Two time-average holograms are shown in Fig. 7.

After Stetson left the institute; he completed the work on rigorous fringe theory in holographic interferometry which he published. [8]

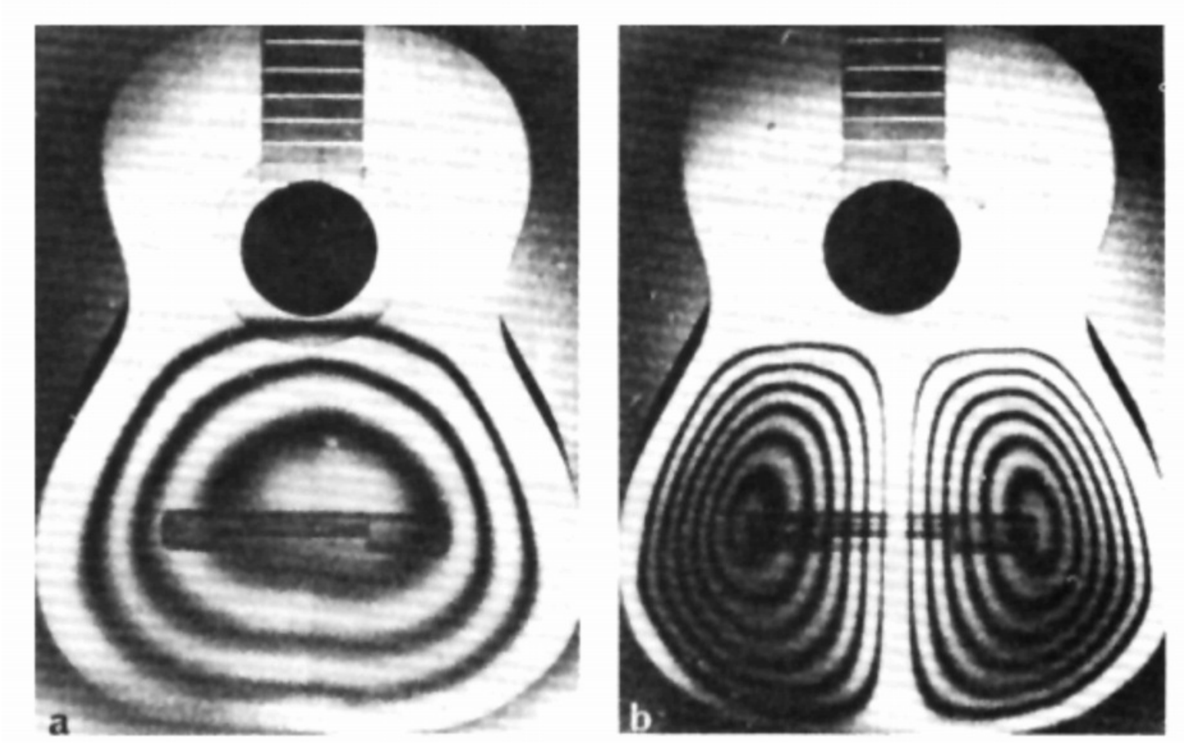
Fig. 7. Time-average holograms of two vibration modes of a guitar

3. Production Engineering Department

In 1967, at the Production Engineering Department at RIT, *Nils Abramson* (Fig. 8), had also started in holography. The work at the department was to study, adapt, and develop methods using the laser in industrial applications. The work was split into two categories: machining and measurement. Measurement was split into alignment, surface inspection, ordinary laser interferometry, and *hologram interferometry.* Hologram interferometry was used for the measurement of dimension, deformation, and vibration. For the department working in mechanical engineering, it was obvious that lasers and holography could contribute to this field.

Nils Abramson introduced the ***HOLODIAGRAM,*** published in five papers. [9-14] The diagram consists of a set of ellipses with the center of the hologram and the illumination source as foci and worked out some elaborate procedures for analyzing the fringes based on this construction, shown in Fig. 9. With the correct geometries, these could depict optical wave fronts. Later Abramson introduced the *Light-in-Flight* recording technique and used this to get into the theory of relativity, etc. This was one of the first observations of a phenomenon that gave rise to what is now called *Optical Coherence Tomography.*

During a 1968 lecture on holography, Nils Abramson demonstrated several transmission holograms he had recorded. One of them was a double-exposed hologram of a two-meter-long steel beam supported at both ends. It was loaded with a 50 g weight in the middle at the left side between exposures. The hologram revealed, through the interference fringes, the minute twist and deformation of the beam, which is shown in Fig. 10.

Fig. 8. Nils Abramson

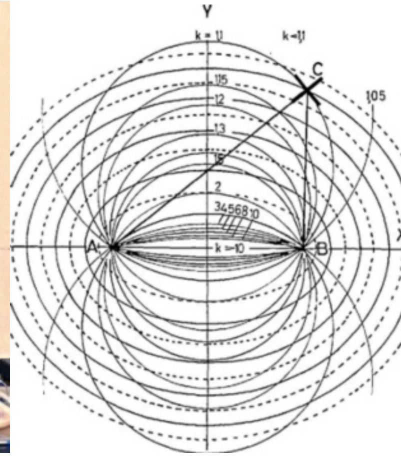

Fig. 9. Holodiagram

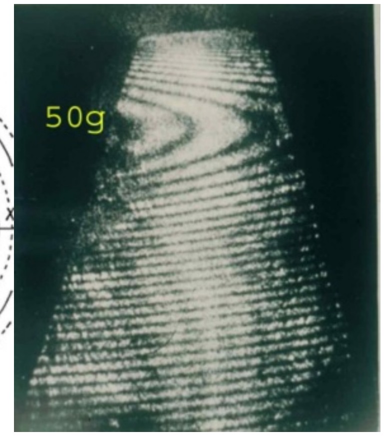

Fig.10. Double-exposed hologram of a deformed steel beam

The author, *Hans Bjelkhagen* (HB), one of Abramson's students, who was interested in photography and had experience in darkroom techniques, decided to start studying holography and joining Abramson's group. In 1969 HB recorded his first hologram in the department laboratory. It was of a measuring instrument with a magnifying glass in front of it. Two views through the 9 by 12 cm transmission hologram plate are shown in Fig. 11.

Within the Mechanical Engineering Department, knowledge about vibrations and vibration measurements existed. Abramson had started to make his holograms *directly on the concrete floor* in the basement laboratory. He pointed out that *air turbulence* around the setup must be avoided during the recording. This was important knowledge we had when the company Lasergruppen Holovision started. The hologram setup was arranged directly on the concrete floor in the basement of the laboratory building. In this way it was easy to record large-format holograms when the size of a table doesn't limit the setup area. Abramson had also started to record holograms of large objects using only a single illuminating beam. Within the expanded illuminating laser light, a *reference mirror* was positioned to send the reference beam to the recording plate. Different types of reference mirrors were used with different degree of reflectivity to obtain the optimal reference-object beam ratio. Using a minimum of optical components and the simplest possible setup resulted in high-quality holograms. An example of Abramson's early holograms of large objects is the milling machine hologram. The double-exposed hologram (Fig. 9) reveals the minute deformation of the big machine caused by the applied force acting between the tool and workpiece [15].

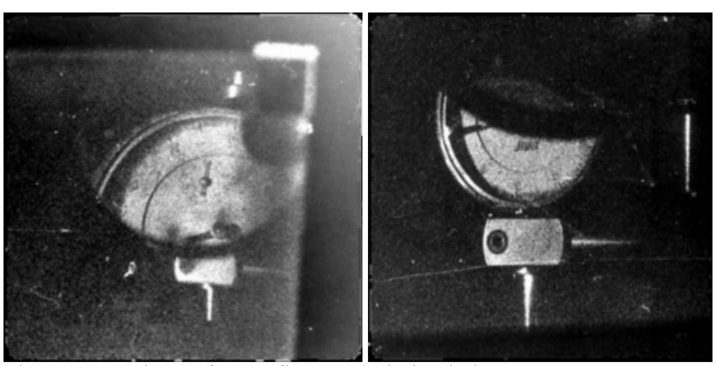

Fig. 11. Two views of HB's first transmission hologram

Fig.12. The milling machine hologram

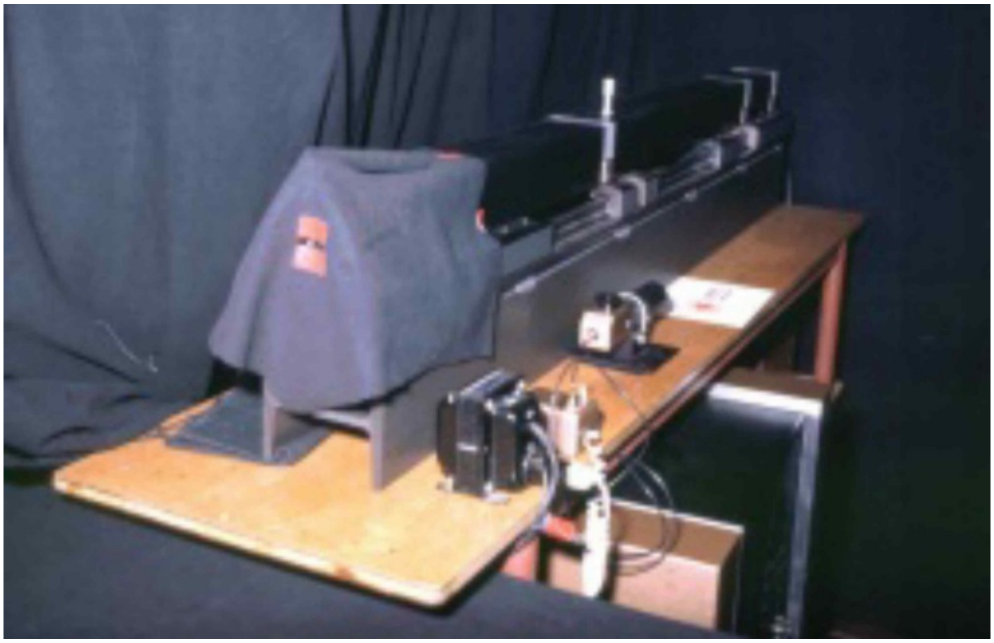

Fig. 13. *HOLOBEAM* ruby laser

A 150 mJ *HOLOBEAM* ruby laser arrived in the lab in 1971 (Fig. 13). It had one ruby oscillator and one ruby amplifier. A Pockels Cell acted as the Q-switch which could be set to generate a double pulse with different delay time between pulses. HB oversaw the laser and devoted a lot of time on pulsed holography applications. First, he made a self-portrait with welder goggles (Fig. 14). Later a setup was arranged for safe recording of hologram portraits. An early demonstration of using it for dynamic measurements was a double-pulsed hologram of a hand drilling machine in operation. The interference fringes reveal the vibration of both the hand holding it and the machine as shown in Fig. 15. The exposure time was 24 ns/pulse with 200 μs delay between the pulses.

Fig. 14. HB Self-portrait (1971)

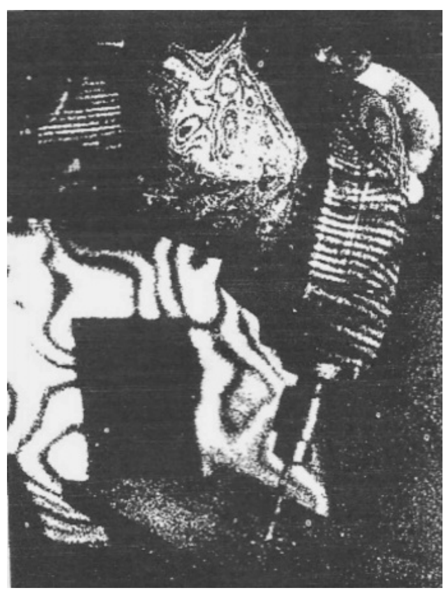

Fig. 15. Hand drilling machine

Fig. 16. VOLVO car floor

Fig. 17. Lasers and holographic recording equipment

A hologram interferometry investigation by HB was to investigate underbody vibrations of a VOLVO car at the factory in Gothenburg. The car floor to be recorded is shown in Fig. 16. The double pulsed HOLOBEAM ruby laser was used to recorded holograms at resonance frequencies. The recording equipment is shown in Fig. 17. The setup used was of the single-beam illumination type with one expanded single-beam illumination of the large car floor. A reference mirror was positioned within the illumination, close to the object. Before the holograms were recorded, a 20 mW He-Ne laser was used to exactly find the resonance frequencies with speckle pattern real-time observations (Fig. 18). A scanning vibration generator was attached to the car floor in one corner (Fig.19). The recordings were performed during the night when no work was going on and with all machinery switched off, including air conditioning. The floor was excited at different frequencies and double pulsed holograms were recorded at resonance frequencies. On of the recorded holograms at frequency 18 Hz is shown in Fig. 20 with the computer-generated resonance illustration at this frequency in Fig. 21.

Fig. 18. The He-Ne illuminated floor

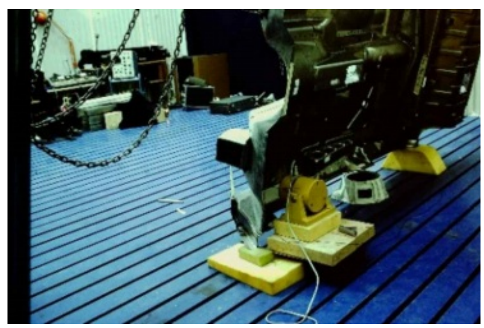

Fig. 19. Vibration generator

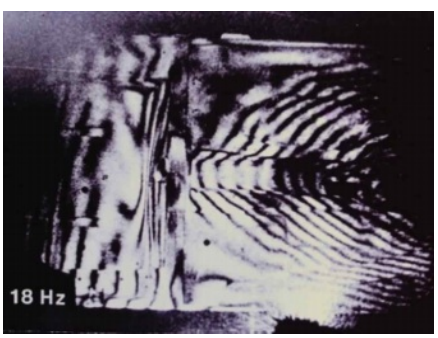

Fig. 20. The 18 Hz hologram

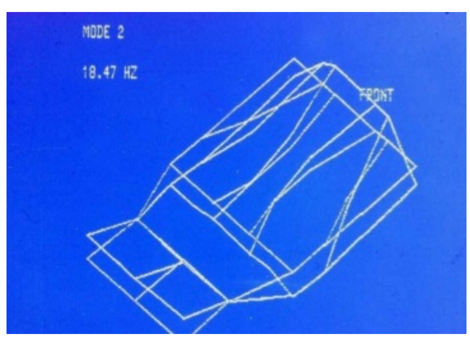

Fig. 21. The predicted frequency

Fig. 22. HB next to the crown recording setup

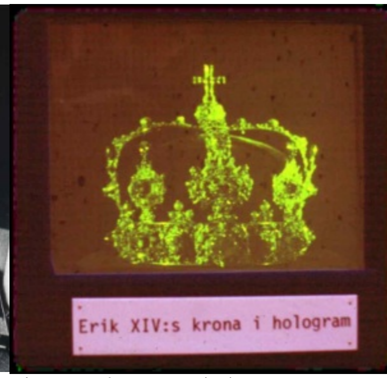

Fig. 23. *The Crown* hologram

Fig. 24. The display case

One early display hologram recorded was the hologram of the Swedish *Coronation Crown of Erik XIV* from 1561. The 20 by 25 cm, off-axis transmission hologram was recorded in the cellar under the Royal Castle in Stockholm during the night of the August 20, 1974. The He Ne laser and holographic equipment were arranged *directly on the floor* in the cellar (Fig. 22). The hologram was produced for the International Stamp Exhibition *STOCKHOLMIA'74* (September 21 – 29, 1974). A postage stamp of the Coronation Crown had been issued in Sweden. The Swedish Post Authority was not allowed to bring the Crown and show it at the exhibition. Instead, they ordered a hologram of it (Fig. 23). At the exhibition, the *Crown Hologram* was installed in a special display case where it was illuminated from the bottom with a mercury-arc lamp equipped with a yellow interference filter (Fig. 24). The hologram was the main attraction at the show and people waited in a long line to be able to get a glimpse of the hologram. Many people, not interested in postage stamps, came to the exhibition only to see the hologram.

An early double-pulsed interferometric hologram project was an investigation of the *dynamics of human teeth* in cooperation with *Paul Wedendal*. The double-pulsed ruby laser was connected to an electronic sub miniature force sensor for pulse triggering (Fig. 25). Force increase and pulse positions were registered synchronously on the screen of an oscilloscope. The corresponding teeth deformations were evaluated by means of the recorded double-pulsed hologram (Fig. 26). This investigation was published in *Applied Optics* in November 1974 and featured on the cover of the journal (Fig. 27). [16]

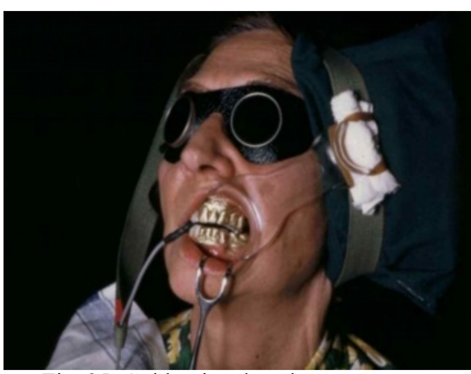

Fig. 25. Gold-painted teeth

Fig. 26. Double-pulsed teeth hologram

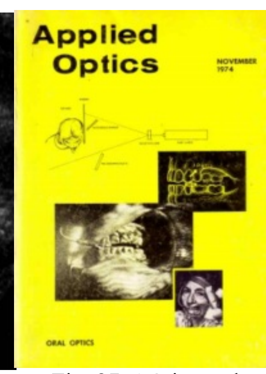

Fig. 27. AO journal

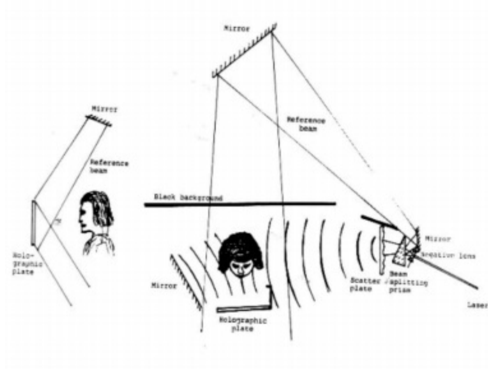

Fig. 27. Hologram portrait recording setup

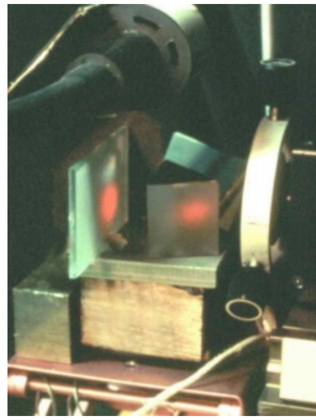

Fig. 28. Beam-splitting prism

Fig. 29. HB next to the laser

Having a pulsed laser, it was, of course, interesting to arrange a safe recording setup for hologram portraits. Ophthalmology professor Björn Tengroth at Karolinska Institute checked the setup from the eye-safety aspect of it. He was also the first person having his portrait recorded after inspecting the setup, confirming it was completely safe. For portraits, only a single pulse is needed, the Pockels Cell was replaced with a Dye Cell filled with a bleaching dye. This resulted in improved coherence length of the laser and higher quality hologram portraits.

Fig. 27 is a drawing of the setup used for the early hologram portraits. After the negative lens in front of the laser, a prism is used. The diverted light passing through it hits a ground glass. The distance between it and the prism is selected to make the diffuse area on the ground glass large enough for the safe illumination of eyes. Fig. 28 shows a photo of the beam splitting optics and ground glass. The about 10% reflection off the front surface of the prism is used to generate the reference beam which is guided to the hologram plate via front-silvered mirrors. A large mirror reflects the light from the ground glass so that both sides of the subject's face can be illuminated. The reference beam reflected by the recording plate is directed down to the floor and not able to reach the recorded subject. Initially, both the masters and reflection copies were recorded on *Agfa HOLOTEST8E75* 8" by 10" glass plates. HB is standing next to the ruby laser in Fig 29. In 1992 he published a paper on hologram portraits. [17]

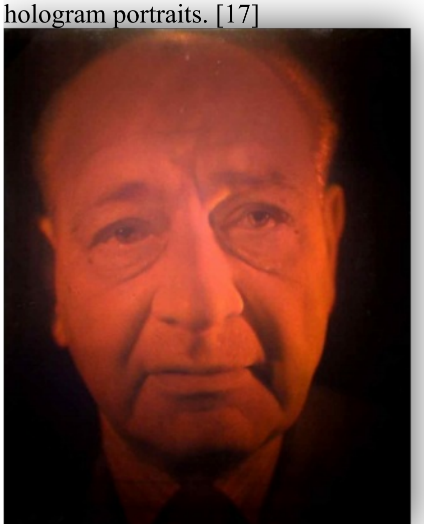

Fig. 30. Albert Bonnier hologram

During the late 1970s several hologram portraits were recorded of famous Swedish people. The transfer setup to get a white-light viewable reflection copy was done in a tranfer setup with a He-Ne laser. The processing of the reflection copy was performed to obtain a yellow-red portrait image.

One early example is the portrait of *Albert Bonnier Jr.*, recorded on May 9, 1979 (Fig. 30).
Albert "Abbe" Bonnier (1907 – 1989) was the chairman of the family-run Albert Bonniers Publishing House which also owned Sweden's two largest newspapers: *Dagens Nyheter* and *Expressen*.

Fig. 31. *Kilroy* art piece and installed in the LHAB lab

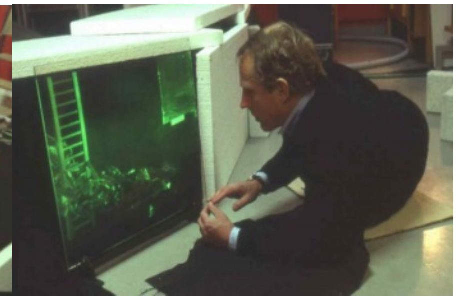

Fig. 32. CFR inspecting the hologram

4. Early display holograms recorded at Lasergruppen Holovision AB

The company was formed by members of the Production Engineering Department. The main purpose of the work was focused on *Display Holography.* The first laser was a 5W Spectra-Physics argon-ion gas laser. The first type of recorded holograms was large-format off-axis transmission holograms. Towards the end of the 1970s the company started to produce several stock reflection holograms after the company invested in a 5 W Spectra Physics krypton-ion gas laser. This laser med it possible to record large-format reflection holograms. Not until the early 1980s commercial display reflection hologram projects took off with many projects for exhibitions and advertising. The advantage was that ordinary spotlights could be used for exhibitions of reflection holograms. This meant that large transmission holograms stopped being recorded. *Lennart Svensson* and *Per Skande* joined the company and after that a pulsed JK ruby laser was ordered. Later, *Jonny Gustafsson* also joined the company. In the late 80s and early 90s the company worked together with *Holicon Corp* in the USA to make transfer copies of recorded hologram portraits at Holicon. Jonny Gustafsson is now the owner of LHAB which still exists but with limited activities nowadays.

5. Carl Fredrik Reutersward Art Holograms

The Swedish artist *Carl Fredrik Reuterswärd* (1934-2016) also known as CFR was an established artist who was very early attracted to lasers and holography. CFR is best known for his Non-Violence sculpture, showing a revolver tied in a knot, located outside the United Nations Building in New York. CFR first contact with a laser was at Bell's Laboratories in New Jersey. There he met Billy Klüver who demonstrated a laser and together they made some experiment using laser beams. In 1963, he got in contact with Per-Ove Stopp in Sweden. Stopp's company, SAVEN AB, imported and sold lasers in Sweden. CFR was able to rent a laser from him. *Nils-Robert Nilsson* at Uppsala University was the first scientist in Sweden who worked with CFR to create laser art. In 1968, CFR used lasers as scene decorations for Ferruccio Busoni's *Doctor Faust* at the Opera House in Stockholm. Towards the end of the 1960's CFR met Nils Abramson in Stockholm. He introduced him to holography and they recorded some small transmission holograms. When HB in 1972 started to work with CFR, they started to record many test holograms together. After that, most of the CFR's art holograms were recorded by HB. These holograms were recorded both at the holographic laboratories at the Production Engineering Department (with the pulsed ruby laser) and at Lasergruppen Holovision AB (with the argon-ion laser). *Kilroy* was CFR's main work over a period of ten years. The art piece itself consists of nine individual pieces: *The Hand, The Seal, The Coition, The Dog's Bone, The Heart, The Ladder, The Eye,* and *The Stone* (Fig. 31). A 50 by 60 cm transmission hologram was recorded of *Kilroy* which CFR inspects in Fig. 32.

Fig. 33. CFR exhibition sign at the entrance of MOH in New York

Fig. 34. CFR exhibition poster

In the installation, part of the art piece is a red He-Ne laser beam illuminating the heart to create a red bright spot on it. The hologram was recorded of the entire art piece on the concrete floor at the LHAB lab as shown in Fig. 31. A separate laser beam was split off from the recording laser, which was directed to hit the heart, so that the hologram also shows a bright spot hitting the heart in the hologram. In the 1970s when the hologram was on display, a mercury-arc lamp equipped with a green interference filter was used for the illumination. It was included in CFR's exhibition: *Kilroy: Holy Holos and Lazy Lasers* at the Museum of Holography in New York in November 1978. (Figs. 33 and 34). The *Kilroy* hologram is now part of the Reuterswärd Collection at Musée National d'Art Moderne in Paris. One very interesting art hologram was the 1978 piece entitled *Smoke without Fire* or *Gateaux Gabor*, a 50 by 60 cm transmission hologram plate recorded at the LHAB lab. The hologram of a cake was made as a tribute to Dennis Gabor, for the 30-year anniversary of Gabor's 1948 paper on holography. This is an interesting example of how an interference pattern can be used by an artist. It was possible to visualize the heat from the burning candles through the recorded interference pattern above the cake. The heat from burning candles created a tremendous 3D "smoke" pattern above the birthday cake. In Fig, 35, CFR and HB show the cake made of wood and with white silicon sealant serving as whipped cream. During the hologram recording, the thirty candles were burning. The light emitted from them (mainly in the yellow-red region of the spectrum) did not fog the green-sensitive 8E56 Agfa plate recorded with a green laser. After the plate was positioned in the plate holder it was covered by a black cloth. The candles were lit and slowly the black cloth was removed not to create any air turbulence in front of the plate. After that, the exposure took place. The setup with a white background behind the cake is shown in Fig. 36 with CFR lighting the candles. A photo of the finished hologram is shown in Fig. 37. This hologram is now part of the MIT hologram collection.

Fig. 35. The cake, CFR, and HB

Fig. 36. CFR lighting the cake candles

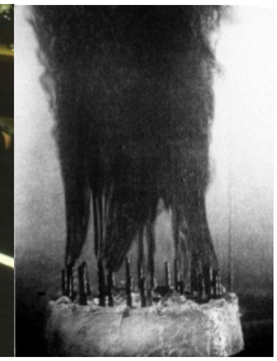

Fig. 37. *Gateaux Gabor*

Finger Language is an edition of four reflection holograms from 1973 depicted in Fig. 38. The four master holograms were recorded of CFR's gold-painted hand with the pulsed ruby laser in 1972. The limited-edition (ten series) was produced in 1973 with the reflection copies recorded with a He-Ne laser. *Kilroy's Heart* from 1975 is another reflection hologram shown in Fig. 39. The gilt bronze heart used for the recording was created from a model in clay from anonymous human heart in New York in September 1962. This bronze heart was used for producing the master hologram with the pulsed ruby laser in 1973. Before recording the hologram, silver glitter flakes were emitted from above the heart, and the laser was fired when they were positioned around the heart. This effect was to simulate stars around the heart floating in space. The limited-edition reflection holograms were produced in 1975. CFR signed his glass plates in the left lower corner using a dentist's drill as shown in Fig. 40.

Fig. 38. The four *Finger Language* reflection holograms.

Fig. 39. *Kilroy's Heart*

Fig. 40. CFR signs the hologram in the lower left corner

6. Display holography in Sweden after the 1970s

A review of early holography in Sweden has been provided in this paper. In the beginning, the main applications were in hologram interferometry for measurement and non-destructive testing. RIT got very well equipped from the beginning, including a pulsed ruby laser, delivered in 1971. With this laser it was possible to perform dynamic recordings, record moving objects and portraits. Towards the end of the 1970s several high-quality display holograms had been recorded at both RIT and in the commercial company LHAB. This also included several recorded hologram portraits of famous people.

In the beginning of the 1980s a fast expansion of display holography took place all around the world. More applications appeared and many commercial display holography projects were carried out. In the beginning, mainly transmission off-axis holograms were recorded. To display them lasers were required or, in most cases, mercury-arc lamps. Therefor the focus became rather early on recording white-light viewable holograms. Mainly *Benton's rainbow holograms* but also *reflection holograms* including single-beam *Denisyuk holograms*started to be recorded. The advantage was that these holograms could be illuminated with ordinary track lighting and spotlights. In the 1980s, hologram portrait studios with pulsed ruby or Nd:YAG lasers were established in America and Europe. Hologram shops and galleries open around the world. A large amount of hologram items and stock holograms were produced for the new market. Mass-production using embossing techniques meant that large quantities could be produce at a low cost. The boom in display holography continued until the mid-1990s. Towards the end of the 1990s many display holography companies, studios, galleries and shops closed. One exception is the document security application of holography which was a successful and profitable business throughout the years. It started as soon as it was possible to mass-produce large quantities of embossed holograms. These holograms were applied to credit cards, passports, ID cards, banknotes, and many other security documents, requiring very large quantities of mainly small holograms. Embossed holograms also appeared on books, magazines, products, and toys to attract customers. In display holography, the interest in rainbow-colored images or monochrome images faded away. The possibility to record color reflection holograms using RGB lasers appeared in the mid-1990s. Such holograms required new materials like the ultra-fine-grain panchromatic silver halide emulsions as well as panchromatic photopolymer materials. Many new small, powerful solid-state lasers exist which contributed to the progress. For example, recording equipment can now be brought to museums for hologram recording. Several analog color Denisyuk holograms for museum artefact documentation and exhibitions have been recorded. In addition, digital techniques have been developed for printing large-format color holograms.

This is where we are today regarding display holography. The question is what will happen in the future is uncertain. Will holography ever become an established world-wide 3D imaging technique?

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Holographic reconstruction of 360° nadar's revolving self portrait

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ABSTRACT

Félix Nadar was a renowned French photographer and a key figure in the history of photography. In 1865, he produced a 360° revolving self-portrait using 12 different photographs. Thanks to the latest holographic technologies combined with artificial intelligence, this research shows that it is now possible, 150 years later, to reconstruct this portrait in 3D as a half-parallax full-color hologram. The experiments were successfully carried out using the CHIMERA digital holographic stereogram printing technique combined with neural network.

Keywords: Digital holographic portrait, CHIMERA, neural network, full-color hologram.

1. INTRODUCTION

Nadar, born Gaspard-Félix Tournachon (1820–1910), was a renowned French photographer and a key figure in the history of photography[1]. He played a crucial role in elevating photography to an art form and shaping its cultural significance. He began his career as a caricaturist and journalist, contributing to various publications of the time. However, his interest in the emerging medium of photography soon took center stage. In the mid-19th century, when photography was still in its infancy, Nadar recognized its potential and explored innovative techniques and applications. He became one of the early pioneers of aerial photography, capturing images from hot air balloons.

Furthermore, Nadar was renowned for his exceptional portrait photography[2]. He photographed numerous notable figures of his time, including artists, writers, intellectuals, and political leaders such as the French writer Alexandre Dumas (Fig. 1a), the French novelist Jules Verne (Fig. 1b), the German-born French composer Jacques Offenbach (Fig. 1c), the French stage actress Sandra Bernhard (Fig. 1d) or Emperor Alexander III of Russia (Fig. 1e). His portraits were characterized by their artistic composition, attention to detail, and capturing the essence of his subjects' personalities. Nadar's studio became a hub for the Parisian intelligentsia, and his photographs were widely celebrated for their aesthetic qualities.


(a) (b) (c) (d) (e)

Figure 1. Five historical portraits recorded by Nadar. French writer Alexandre Dumas (a), French novelist Jules Verne (b), German-born French composer Jacques Offenbach (c), French stage actress Sandra Bernhard (e), Emperor Alexander III of Russia. (Public domain images)

Around 1865, Nadar produced a series of self-portraits consisting of 12 images showing different angles of him sitting in a chair, as shown in figure 2. Each image is separated by 30°, for a total rotation of 360°. With the exception of a smile in one image, not even a crease in his jacket or a hair appears to change from one angle to the next. This rotating self-portrait, also known as the Nadar's Revolving Self-Portrait, is a remarkable photograph that could be considered a predecessor of the chronophotography that Marey, Muybridge and Londe[3] began experimenting with over a decade later.

As the sequence revolves around space rather than time, it is even closer to the "bullet-time" effect popularized by the film "Matrix"[4] some 135 years later. This rotating self-portrait, can also be seen as the predecessor of the 3D scanner[5].

Figure 2. Nadar's Revolving Self-Portrait consisting of 12 images showing different angles of him. (Public domain image)

In 2023 Gentet et al.[6] showed that ultra-realistic, full-color, and full-parallax snapshot holographic portraits can be recorded using multiple synchronized cameras. Experiments were successfully conducted using the digital CHIMERA[7] holographic stereogram printing technique combined with image interpolation using a neural network. Only seven cameras, separated by 20°, were required to record a 120-degree half-parallax portrait. The aim of this research is to apply this technique to Nadar's 12 original photographs to reconstruct this portrait in 3D as full-color digital hologram.

2. MATERIALS AND METHODS

2.1 Materials to record CHIMERA

CHIMERA holograms were recorded on a silver halide holographic Ultimate U04[8] glass plate. This material was specially designed for recording full-color holograms without any diffusion and was set to be isopanchromatic for all visible wavelengths. The plates were developed in two safe and easy-to-use chemical baths.

2.2 CHIMERA recordings

Half-parallax CHIMERA were created by recording a series horizontal perspective images—until 768—on a circular arc—until 120º. In-house software generated all hogels from the perspective images. Each hogels was recorded sequentially using an RGB display system made of three spatial light modulators (SLM) and a 120° full-color optical printing head. After interference with the reference beam, the information corresponding to each RGB hogels was recorded in U04 plate. The hogel size was 250 µm and the printing rate was 60 Hz. The CHIMERA holoprinter used three RGB DPSS 20 mW lasers. The wavelengths were 640, 532, and 457 nm.

2.3 Sealing and illumination of CHIMERA holograms

To reconstruct the CHIMERA holograms to the same wavelengths used when recording, and to prevent any emulsion thickness variations due to changes in humidity or temperature, they were sealed with a second glass using optical ultraviolet (UV) glue. RGB light-emitting diodes (LED) currently offer the best solution of illumination because their wavelengths are centered on laser wavelengths[9].

2.4 Cleaning of the source images

The source images, very old and with a low resolution, were previously cleaned by the hand of their stains and scratches using GIMP software[10]—a free and open-source raster graphics editor used for image manipulation and image editing—one after the other.

2.5 Colorization of the images

A computer can be train to understand the colors of the different objects by providing a large of amount color photos, then ask the computer to colorize by identifying plausible colors. Thanks to the development of deep learning it was done by using a Generative Adversarial Network (GAN[11]). The various images were colorized using artificial intelligence specially developed by Gentet et al.[12] to colorize pulsed portraits.

2.6 Up-scaling and face correction

Thanks to a second program based on artificial intelligence (AI), source images with too low a resolution (524×671 pixels) could be enlarged and faces restored and enhanced.

2.7 Image interpolation

Frame-interpolation synthesizes intermediate frames between two input images. These are frequently used to produce slow-motion videos. Recent techniques based on a new neural network approach have provided impressive results for large-motion interpolation. An in-house software installed on a fast graphics computer automatically interpolated pictures between two input images. Gentet et al. Experiments show that the interpolated images remain consistent to the original images for rotation angles up to 20°.

3. RESULTS AND DISCUSSION

3.1 Cleaned images

The twelves images were cleaned by the hand, one after one, of their stains and scratches with Gimp software as shown in Fig. 3. Thanks to this cleaning, the following restoration operations will be easier to carry out.

Figure 3. Cleaning of the 12 source images with GIMP.

3.2 Colorization

The twelves images were colorized with an in-house deep learning software. After colorization, the portraits kept a vintage look and pastel colors as shown in Fig. 4.

Figure 4. The 12 colorized images with AI.

3.3 Up-scaling and face correction

Each image was up-scaled from 524×671 pixels to 1320×1760 pixels and the face was enhanced with the in-house AI as shown in Fig. 5 with image number 7. While retaining an old-fashioned look, the portrait gains in realism.

Figure 5. Up-scaling and face correction of image 7.

3.4 Image interpolation

An in-house software interpolates 129 images between each pair of images. An example is shown in Fig.6. As interpolation is carried out between images separated by a wide angle (30°), it is sometimes very difficult to achieve perfect results and creates small defects in the images.

Figure 6. An example of image interpolation with AI between frame 4 and 5.

3.5 Holograms

Hogels were then generated from these images and recorded with a 250 µm resolution one after another into 10×13 cm U04 holographic plate. Hologram was then developed using two chemical baths and sealed with optical glue to prevent variations in the emulsion thickness. When the CHIMERA was illuminated 50 cm from the center of the hologram and at an angle of 45° with an RGB LED lamp, a fine color and half-parallax reconstruction of Nadar in 3D was generated, as shown in Fig. 7. Although the reconstruction is not perfect, with the portrait appearing slightly distorted at certain angles, the overall look is particularly striking and realistic.

Figure 7. A 10×13 cm sealed CHIMERA portrait of Nadar illuminated with an RGB LED lamp.

4. CONCLUSION

Thanks to the combination of CHIMERA technology and the latest advances in artificial intelligence, it has been possible to reconstruct Nadar's self-portrait in 3D as a color hologram from a series of photos taken over 150 years ago.

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Preserving display holography: what to keep, where, and why?

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ABSTRACT

This academic paper presents the findings of a project aimed at cataloguing and preserving holographic pieces in a private collection. The holograms were created by the late Robert and Molly Gibson: hobbyists who left a large body of artwork given to the author. The study delves into the central question of what work should be kept and what should be discarded as part of a holographer's legacy. In conducting this research, the author utilized in-depth interviews with artists and collectors to gain insights into the issues surrounding artwork preservation and legacy. The paper's primary argument suggests that while preserving all artworks is desirable, it is important to develop appropriate criteria for selecting which pieces should be kept, as not all works will have equal significance or value. By examining the case of the Gibson's holographic collection, the study highlights the importance of considering the artist's intent, uniqueness of the art piece, and its individual significance in preserving an artistic legacy. The paper concludes with recommendations and implications for hobbyists, art professionals and collectors regarding best practices for future art preservation and legacy projects.

Keywords: collecting, creative holography, museums, conservation, preservation.

1. INTRODUCTION

The paper describes a collaborative project between an artist (John) and a scientist (Cook), who were brought together to preserve, conserve, and disseminate a collection of holograms made by the late Bob and Molly Gibson (1931–2021, 1933-2021) (shown in figure 1). Display holography has been in development since the invention of the laser in the 60s and since then holograms – as objects - have proliferated. The author (John), an artist and an educator, has been making holograms since the mid-1980s and has amassed her own collection of marketing and security holograms, holographic sketches, tests, and artworks. However, as someone responsible for clearing the personal effects of deceased family members, John has become acutely aware that her family will be left to deal with her own collection. This project explores the personal question critical to the fate of holography collections: where should a collection go to ensure it is seen and appreciated by as wide an audience as possible? The Gibsons were hobbyists who made holograms both as a couple and independently to create a diverse collection of holographic artworks, leaving a collection to their family including master holograms and transfers, tests, and final pieces. This paper details the processes the authors took to examine, document, and catalogue each piece to help develop criteria to determine which pieces should be kept for posterity.

The audiences for the paper are hobbyists, students, and emerging artists. To answer the question of what to keep and what to throw away - the project has included the careful examination and documenting of the collection, and an analysis of the advice provided by specialists, i.e., Artist and Technologist Emeritus Professor Martin Richardson, formerly of De Montfort University, and Gallery owner and collector Jonathan Ross. The authors also reviewed the collecting and preservation policies of the London Science and Victoria and Albert (V&A) Museums and corresponded with a curator Rupert Cole, at the Science Museum. Both museums are in discussion with Richardson and Ross about acquiring their holography collections. The paper ends with recommendations on how to conserve and preserve holograms to disseminate them as widely as possible.

2. METHOD

This section briefly describes how the author (John) acquired a collection of holograms produced by the Gibsons from one of their sons – John Gibson - after their deaths. In her PhD Dissertation in 1994 entitled *How Is Holography Art?* the pioneering UK artist Margaret Benyon defined different types of Holographer and Holography: *Creative holography: someone who uses the process in a creative way, not just as a technical* *recording process, but who need not be an artist.*[1] Benyon argued that the title of 'artist' be reserved for someone professional with a corresponding tax status. The Gibsons are therefore described as Hobbyists or Creative Holographers for the purposes of this project.

Figure 1: a) Creative Holographers Bob and Molly. b) Molly Gibson. Photographs provided by John Gibson.

In April 2022 John Gibson contacted the author offering her a gift of unexposed boxes of 'vintage' Agfa plates produced in the mid-1990s. As John was still using Agfa film for her artwork she eagerly accepted, offering to share the boxes with students. The boxes, shown in Figure 2, were collected from the Gibson's, and contents carefully examined under safelight in John's lab at the University of Southampton, where it was revealed that the boxes contained artwork rather than unexposed plates. From there, with the help of India Cook, a PhD student of Physics, each piece of artwork was documented, photographed, and categorised. Further correspondence with John Gibson led to the author being shown lab books and more of the Gibson's finished pieces.

Figure 2: a) Agfa 8" x 10" plates and b) 4" x 5" Holography boxes gifted to the author. Photographs by John Gibson

The 12 boxes were found to contain 121 holograms: 101 exposed glass plates and 8 film holograms. 13 of the holograms were either very damaged or did not contain a visible hologram. The remaining 108 holograms were catalogued as shown in table 1. Each hologram was numbered by the holographers with small circular stickers. However, the position of stickers did not always follow the labelling convention of being in the top right-hand corner which prevented easy identification and viewing. Most of the holograms (71) were transmission masters and were later identified as being elements of creative works produced as part of the preparation for an application of a Royal Photographic Society (RPS) award. The imagery included folded card shapes – produced by Molly, and shaped metal work such as springs. As Molly had a background in crafts, and Bob in Engineering, their subject matter seemed appropriate. A sample of the transmission holograms are shown below in figure 3.

Table 1: John and Cook's Summary of the acquired holograms:

Number	Substrate	Size	Type of Hologram
66	Glass plate	8 x 10	Laser Transmission
21	Glass plate	8 x 10	Reflection
5	Glass plate	4 x 5	Laser Transmission
9	Glass plate	4 X 5	Reflection
8	Film	8 X 10	Reflection
Total = 108			

The Gibsons used a red, Helium Neon Laser, producing laser transmission and pseudo-colour reflection transfers using a pre-swelling technique with Triethanolamine and multiple exposures on the Agfa, Silver Halide Holographic materials. This process was carefully documented as seen below in figure 3. In the early 1990s they achieved their qualifications from The RPS which acknowledged their skill and creativity. The RPS required applicants to submit a work/project of 20 images – some of which are illustrated below in figure 4, with a supporting written Statement of Intent and a Presentation. The body of work had to be cohesive and communicate the aims and objectives set out in the statement of intent. The work also had to demonstrate a high level of technical ability craft and artistic presentation.[2] According to their logbooks shown in figure 5 the Gibsons honed their craft from 1986-1991 in order to produce their holograms for the RPS qualification.

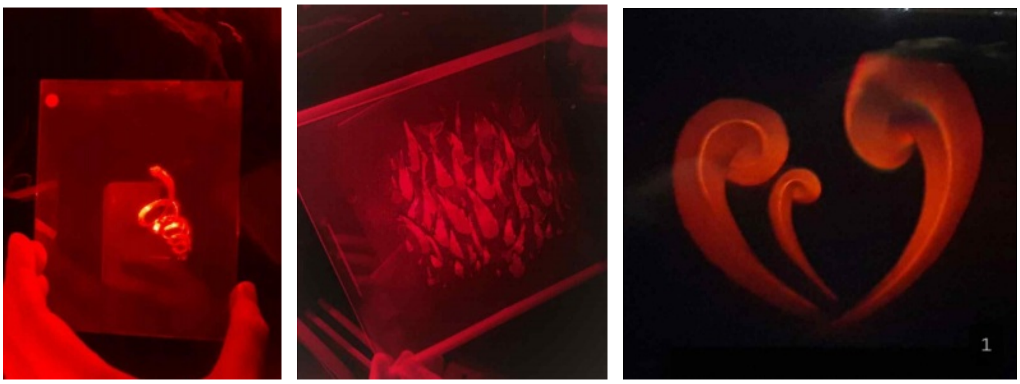

Figure 3: a) Transmission Master hologram *Spiral Coil left* b) Transmission Master hologram L*eafy Background* and c) Reflection Transfer *Mother, Father, and Child*. Photographs by the authors.

2.2 Analysis of Holograms

After inspecting the contents of each new box under safelight to confirm that all the holographic plates had been exposed, we meticulously inspected and categorised each hologram according to quality and artistry. Each piece of artwork was evaluated according to four criteria: i) physical damage, ii) objective [technical] quality of the hologram, iii) uniqueness and iv) subjective artistic merit, our assessment of each of these criteria is detailed below:

i) Physical damage. Some of the holographic plates suffered physical damage from fungus growing on the storage boxes and on the holographic plates themselves. Where possible, mould was removed, although in some cases this process caused further damage to the artwork. Further discussion on conservation and mould prevention can be found below.

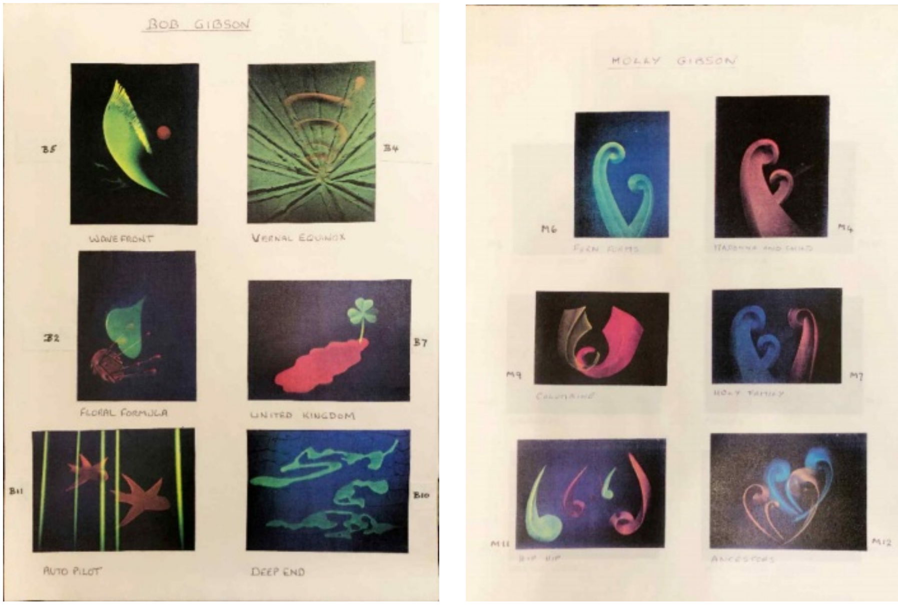

Figure 4: Catalogue documentation for the RPS qualification. a) Bob Gibson's and b*)* Molly Gibson's

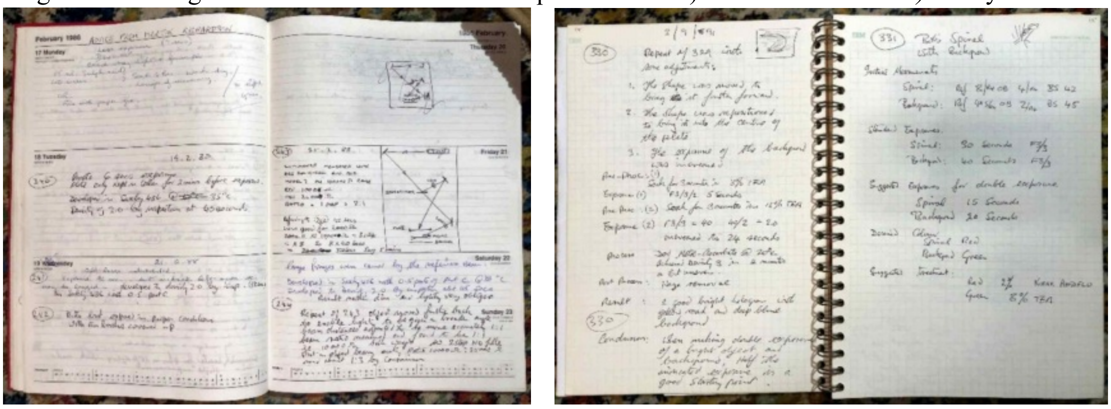

Figure 5: The Gibson's logbooks. Photographs by John Gibson.

ii) Objective quality of the hologram. Amongst this collection of holographic artworks were many iterations and tests of various colours/exposures/ depths. Naturally, imperfections were abundant. The objective quality of each hologram was assessed by considering the brightness and clarity, with any damage such as overexposure, or movement.

iii) Uniqueness. This hologram collection included many iterations of the same artwork. We made the decision to keep only 2-3 copies of any given hologram.

iv) Subjective artistic merit. This criterion posed the most difficult challenge in assessing the merits and fate of each piece of artwork. Here, Cook and John did not agree. There were several holograms with a more commercial than creative approach which John thought had less merit.

2.3 Outcome

Using the criteria detailed above, we decided to keep or discard each hologram. Amongst those we decided to keep, we dually categorised each plate according to the type of hologram (e.g., single or double exposure reflection, or transmission), and build a database inventory of all holograms inclusive of number, [Invented] title, notes on condition, type of hologram, destiny (keep/discard). Additionally, we identified a selection of the most impressive holograms that could be used to showcase the artwork to prospective curators and collectors.

Table 2. Example summary of documentation approach.

Transmission Master Box 6		Reflection Box 1		Best Works Box		Discard	
Image	#	Image	#	Image	#	Image	#
Corner Cornice	496	Sea wave	416	(TM)Carmen with Dancer	461	Spiral Coil	404
Corner Cornice	497	Mother and Child	421	(REF) Mother And Baby	464	No Image	410
Mother and Daughter	498	Heart (2 Curly Qs)	468	(REF) Family of 5 Curly Qs	465	Colour Test	420
Road into the distance	499	3 X Mobi Strip	478	(REF) Vertical rod and approx. sign	472	Heart	469
Squiggly Background	500	Double Sweep	481	(REF)Husband and Wife not talking	493	3 X Mobi Strip	479
Deep End/Spiral Galexy	521	Yellow and Blue Curls	483	(REF) Mother and Child	505	3 X Mobi Strip	480
Deep End / Spiral Galaxy Background	522	Red eye - Green Fresnel	489	(TM)Leafy background	526		
Dull Surface of the moon	523	Husband and Wife not Talking	494	(REF) Pirate of Penzance	528		
Plastic circles	524	(FILM) Green/Orange Background	7	Deep End/Spiral Galexy Background	520		
Leafy background	525	(FILM) Blue/Green Background	2	(TM)Fresnal Lens	513		
		(FILM) Bluesish Background	11	(REF)Fresnal LEns	512		
		(FILM) Reddish background	10	(FILM) (REF) Hip Hop Foreground	1		
		(FILM) Reddish background	9	(TM)Holly Leaf	196		
		(FILM) Green/Yellow Background	6	Vernal Equinox coil red	169		
		(FILM)Yellow	4				
Total	10	Total	8	Total	12	Total	6

3. Collection Policies

There appeared to be five potential destinations for holography collections in the UK; the Collector Jonathan Ross, owner of Gallery 286; The Science Museum; The V&A Museum, the Royal Photographic Society (who are just beginning to collect works) and De Montfort University who have an archive. The Science Museum and The Victoria & Albert Museum have impressive holography collections as well as well-established criteria for acquiring items. Within this project, we interviewed holography specialists Professor Martin Richardson and Ross to refine our criteria for assessing the quality of the holograms to determine which may be best suited to the different museum collections, we also corresponded with a Science Museum Curator Rupert Cole. Following our efforts sorting and catagorising the collection, our next challenge was to disseminate the artwork for preservation and display.

Both Richardson and Ross have made provision to ensure that their own collections will be housed in the Science Museum and the V&A Museums, respectively. The Science Museum acquires not only display holograms, but the technology used for holography production too. On his retirement from De Montfort University Richardson realised that he had a collection of ~750 holograms which he had carefully documented since the mid-1990s when John had acted as his assistant at The Holographic Image Studios (T.H.I.S). Richardson has donated work and technology throughout his 40-year career to the Science Museum and is happy to have his work homed in a context that emphasised the science and the technology, rather than the art:

> *I still think holography is in that infancy stage where it's not recognized as an Art and I'm OK with that, I'm comfortable with the work being seen as scientific endeavors, and it's for future generations to decide.* (Richardson, M., Personal Communication with John, P., 27 May 2023).

The primary goal of the Science Museum is to educate and inspire people, specifically young people, in science-themed content. Therefore, its collection policies aim to acquire content that educates and offers visitors insights into scientific developments and the process of innovating in science and technology.[3] The Museum values holographic artwork as it serves both as an educational tool and means of exploring interdisciplinary knowledge. However, Cole wants to acquire "things that have compelling stories of use". Richardson has always been both an artist and a technical innovator and has made holograms and portraits of the famous including the musician David Bowie, the artist Peter Blake and film maker Martin Scorsese, amongst others. Rupert Cole, Curator said of his work:

> *I judged that Martin Richardson was a figure of national importance in regards to holography, an area that has been underdeveloped in our collection since the 1980s.* (Cole, R., Personal correspondence with John, P. 6 June 2023).

The Science Museum will be taking Richardson's entire collection which is headed for storage for six months after which time Richardson would be photographing the holograms and filming them for a website.

Ross's collection too relies on a web archive that makes his large collection accessible to the public.[4] (Although it is always difficult to display three-dimensional works on-line). In our interview Ross was keen for artists and holographers who had works in his collection, to supply him with information about their art to help provide more context. This information will be beneficial for the long term when the collection is transferred to the V&A as the institution aims to promote and preserve art and design in all its forms.[5]

3.1. Artistic Merit

John and Richardson discussed how to determine the artistic merit of a piece. While it could be argued that an artwork should stand on its own merits – museum staff who had not been trained in holography could not be expected to necessarily know the difference between a good and bad hologram and would benefit from support by qualified holographers. There was also the issue in display holography that a good hologram technically might not be a good artwork and a good piece of artwork might not appear to be a good display hologram. We would usually describe a suitable display hologram as containing suitable subject matter for holography, be well lit and accessible to audiences:

> *It's a very interesting discussion...: what makes an interesting hologram? If you had to make a choice between a perfect hologram... and something like let's say for example Carl Fredrik Reuterswärd's Birthday cake [1978 piece entitled Smoke without Fire/ Gateaux Gabor]* [6]*, it would be the latter for the plumes of smoke.* (Richardson, M., Personal Communication with John, P., 27 May 2023).

The artwork – a laser transmission hologram - produced with Hans Bjelkhagen's technical support was made in the Lasergruppen Holovision AB (LHAB) in Stockholm relied on a technical limitation in holography – that light and movement cannot be recorded. Dark areas in a hologram usually indicate a problem with a display hologram. But the fire – light/heat and movement in the artwork caused an absence of image and conversely the highlight presence of fire. The image is fascinating. Reuterswärd exploited the limitations of the medium for creative purposes.

Rather than focusing on the merits of individual artworks, The Science Museum collects items of historical significance in contemporary material which represents the practice and process of science. Having Richardson's whole collection – along with some of his technical equipment – better represented the practice and process of holography as it developed over the period. (Cole, R., Personal correspondence with John, P. 6 June 2023).

3.2. What won't be collected?

In discussion with Richardson, Ross, and after a review of the Science and V&A Museums' collecting policies, it was clear that damaged work, or work which might quickly degrade, would not be collectable. In addition, Ross declared that while he did own some laser transmission artworks - due to the difficulty of lighting and displaying a laser transmission in an exhibition environment - he would be unlikely to want to collect more, especially if the holograms were only tests or masters for transferred artworks. After discussion with the Science Museum Curator about what would be collected, it seems unlikely that thy would want to take on the Gibson's holograms because of lack of evidence of historical significance of the work by the creative holographers.

3.3 Conservation and Preservation

Accreditation is a vital aspect of museum operations, and it specifies the minimum requirements that a National Museum aims to achieve. Requirements specify that a museum should acquire their collections ethically and ensure proper maintenance of the pieces to preserve their value. The Museum of Ontario defines the differences between conservation and preservation – and as the Science Museum and V&A adhere to international Museum standards the definition is relevant.:

> *Conservation and preservation are two methods used to maintain an object's state. Conservation is the hands-on act of working directly with the object to preserve its current condition. Such method can be invasive, for example, conservators use restoration treatments to enhance the*

object to its original state or appearance by removing accumulated layers of dirt and/or adding necessary components that have gone missing.7

Preservation, however, is non-invasive. It aims to prevent an object's condition from deteriorating. Preservation actions include:

- Housing the objects in an environmentally controlled storage facility (i.e., being aware of possible humidity, light damage, etc.)
- Monitoring the collections space bi-weekly and monthly for possible pests
- Practicing appropriate artifact/artwork handling
- Storing the objects in archival boxes with archival materials (materials that preserve the quality and longevity of the object, such as acid-free tissue).

Ross pointed out that changes in temperature and humidity can lead to colour change or even an image disappearing (as had happened with one of John's holograms that had been exhibited in a damp gallery).

Unfortunately, the gelatin coating of many of the Gibson's holograms had succumbed to pests – in our case - mould (figure 6). It is critically important that mould is not present amongst holograms intended for storage and display given the potential risk of its spreading and compromising the integrity of other artwork in the proximity. Further information from the Museum of Ontario site explains the problem of mould in more detail:

> *All organic and inorganic surfaces can be colonized by moulds under the right conditions of high humidity and dispersion of nutrients. Damp cellulosics (paper) and proteinaceous (parchment) materials are the most affected because they are entirely digestible, relatively soft, and can be hard to clean at the porous cellular level where microorganisms contaminate an object (e.g., invasive fungal hyphae, tiny spores with strong pigmentation). The actions of the hyphae stain and digest objects (Figure 6.b).*[7]

The authors did not know what type of fungus had been growing on the box and holographic plate, and therefore what potential damage the mould might do. Where possible, we carefully removed the dust from the glass side of the holograms with a glass cleaner and removed the mould on the box using antifungal spray. Although this process is essential for preservation of holograms, necessary chemicals also pose risk of irreparable physical damage of the holographic plates. Some plates were discarded not only due to mould damage, but also where the act of removing mould caused further physical damage.

Figure 6: a) Agfa storage boxes with mould, Photograph by John Gibson. b) Master hologram with mould. Photograph by India Cook.

In reviewing the preservation guidelines listed above we realised our handling of the master holograms was not best practice – we should have been wearing cotton gloves to protect the plates from getting fingerprints – or oil and dirt on them. We will change our handling procedures as a result.

CONCLUSION

Whether a small personal collection or a large-scale internationally sourced curation, almost all artworks will outlive their 'owner.' This project has highlighted the importance of robust cataloguing methods and the use of established conservation and preservation techniques for the longevity of the art. In the context of holography, conventional cataloguing techniques such as numbering and positional labelling, facilitate the analysis and interpretation of artworks by future curators and collectors. The artworks should be documented through written and photographic means – including filming - retaining context such as exhibition and marketing material, all of which should be digitised for the web to ensure increased audience access.

For the physical preservation of artwork, consideration of storage conditions is essential. The fungus found growing on the Gibson's collection of holography saliently highlights the importance of dry storage conditions. The authors recommend that students and hobbyists consider the long-term preservation and conservation issues around producing their holograms. To have any hope of an individual or public museum wanting to collect or acquire the work it should be kept wherever possible, in conditions without damp or humidity which may change the colour of the work or destroy it entirely.

Further research on the collection is required. The author will recommend to the family that Jonathan Ross be given some of the reflection holograms that he has shown interest in – for the purpose of ensuring long-term and potential for widest dissemination of the work as Ross's collection will eventually be transferred to the V & A. This paper will accompany the hologram, along with as much documentation as Ross is willing to take. Further investigation as to whether the Science Museum would take the laser transmission holograms will be undertaken. Failing that, a local museum without a previous history of collecting holographic art will be approached.

Further investigation into the species and properties of the fugus found on the Gibson's holograms is also required to determine the full extent of risk posed to holography collections. The authors will try to use microscopic techniques to better characterize this fungus' impact on holographic artwork over time.

Finally, central to the concept of artwork preservation, is the notion of sustained enthusiasm for a given artistic medium or theme over time. This project not only detailed a process of preserving artwork that may inspire future artists and scientists, but also demonstrated the merits of involving early career researchers in the process of preservation itself. For example, India Cook, a PhD student of physics – new to holography - made the following personal reflections on completion of this project:

> *'Toiling away in a small dark room, numbering, categorising, cleaning mould, may sound mundane at best…. Yet this could not be further from my experience. When the first transmission hologram caught the laser beam at just the right angle and a bright red coil lurched to life in three-dimensional space – I was hooked! Hours passed unnoticed; I was entirely engrossed in 'discovering' each hologram. Each piece of artwork reveals a moment from the past, trapped in a physical form, unveiled only under precise conditions. I impatiently look forward to learning more about the world of holographic artwork.'*

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Rupert Cole

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TRACK 5.

Recording Materials and Processing

Recording of volume phase gratings in lithium niobate crystal and in germanate fiber using excimer nanosecond UV laser and phase mask

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ABSTRACT

The recording possibility of holographic Bragg gratings of the refractive index in lithium niobate crystal and in germanium-silicate optical fibers with elliptical strain cladding is shown. Structure's recordings were performed by using an excimer nanosecond laser in both single-pulse and multi-pulse sets. A quartz phase mask was used as a beam splitter. The grating's diffraction efficiency and the induced modulation of the refractive index were calculated.

Keywords: Bragg grating, lithium niobate, germanium-silicate optical fiber, phase mask, excimer nanosecond laser

1. INTRODUCTION

Holographic phase volume Bragg grating is a grating of modulated refractive index. These are recorded in photorefractive volume media such as polymers [1,2], glasses (for example, photo-thermo-refractive glasses) [3], crystals (for example, lithium niobate (LN)) [4], etc. Photorefractive polymers like Covestro's Byfall HX [1] or DuPont's OmniDex [2] and similar have rather flexible and elastic transparent film substrates (e.g. polyethylene terephthalate, polycarbonate, cellulosic triacetate, amorphous polyamide, etc.) with relatively thin photorefractive layer on it (less than 100 µm overall). Compared to photorefractive solid media such as glass or crystal, these thin films have an increased influence of coefficient of thermal expansion (CTE). Therefore these films have issues during hologram recording and bleaching processes such as thermal shrinkage and so-called thermal fringes [1]. All this may further lead to unacceptable optical aberrations during recorded microstructure usage in the reconstruction/reading scheme.

In this work we show the possibility of holographic Bragg gratings recording inside LN crystal and germanium-silicate (germanate) glass (optical fiber in particular) by pulsed UV irradiation and phase mask. The usage of pulsed lasers allows to increase the power density. Phase mask allows to simplify and shorten beamsplitter optical scheme and therefore particularly liberates laser beam quality restrictions.

2. METHOD AND EQUIPMENT

2.1 Method and equipment of Bragg gratings recording in LN crystal

LN is well known as a nonlinear pyroelectric and ferroelectric crystal [4,5]. In order to record Bragg grating in this crystal, it needs first to illuminate it within the wavelengths that correspond to its absorption and photosensitivity spectra. LN crystal has highlighted absorption in the UV region [6]. We used a clear non-doped LN crystal substrate with 30 x 15 x 1 mm size and Y-cut as a sample. Excimer nanosecond UV laser Lambda Physik Compex 102 was used as a light source. KrF gas mixture provides a laser irradiation wavelength of λ = 248 nm where LN has high absorption [7]. The laser emits 20 ns pulses at 1-20 Hz tunable frequency (repetition rate) with up to 300 mJ pulse energy. Laser beam has rectangular shape with 24 x 8 mm FWHM size and 3 x 1 mrad spatial divergence correspondingly.

Optical scheme of the setup for Bragg gratings recording in LN crystal is shown on Figure 1.

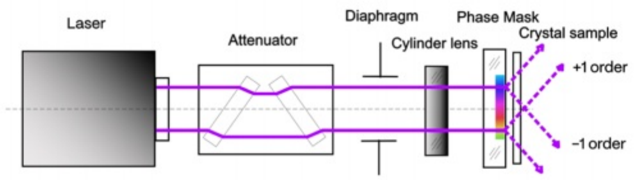

Figure 1. Optical scheme of setup for Bragg gratings recording in LN crystal.

In this linear and compact recording scheme laser beam irradiation firstly passes through manually tunable attenuator to control and tune the laser beam power. Then it comes through special diaphragm and cylinder lens and hits phase mask. It splits into two diffractive orders: +1 and -1 diffractive order. Diffractive beams interfere and illuminate crystal sample which is close (surface-to-surface) to the output surface of the phase mask (possible air gap is less than 100 microns). Attenuator optics, cylinder lens and phase mask substrate are made of quartz glass and so are transparent in UV region (without AR coating). Diaphragm is needed for defining the irradiated area on the sample (and so the recording grating size) and makes spatial filtration since light power distribution at the edges of the laser beam is not uniform (see Figure 1). Cylinder lens CYLX-40×40U-500 (Lambda Research Optics) with 500 mm focal length compresses the beam along the long axis in order to increase laser fluence on the phase mask. Such combination of diaphragm and lens provides 9 x 4 mm hologram size of recorded hologram with up to 800 mJ/cm^2 laser fluence (F) on the phase mask without attenuator. The attenuator weakens laser fluence on the sample surface in the range from maximum available F down to 80 mJ/cm^2 on the phase mask. Phase mask (Ibsen Photonics) has 10 x 25 mm size and d_{pm} = 1065.3 nm period phase grating which in this setup located close to second surface of the sample. Vector of phase mask is situated along the short axis of the laser beam while cylinder lens compression is performing along the long axis of the beam. Phase mask were designed and optimized to hold down to < 3% a zero-order beam. It has 37 % diffraction efficiency in both +1 and -1 diffractive orders on relevant wavelength (λ = 248 nm) and 74 % total diffraction efficiency in first orders.

The phase mask diffraction obeys Bragg's law:

$$2d\sin\theta = m\lambda \qquad (1)$$

Where d = d_{pm} – grating's period, θ – the Bragg's angle, m – diffraction order, λ wavelength of incident light (Bragg's wavelength). According to this, the Bragg's angle of the diffraction is θ = 6.7 ° (m = 1) at λ = 248 nm. Since the Bragg's angle of the diffraction matches the Bragg's angle of incident light to the sample, period of the recorded structure will be the same as phase grating's period (d_{pm} = 1065.3 nm) with other things being equal.

Optical scheme of the setup for Bragg gratings measurement in LN crystal is shown on Figure 2.

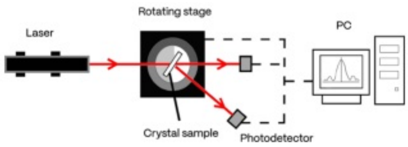

Figure 2. Optical scheme of the setup for Bragg gratings measurement in LN crystal.

He-Ne laser with λ = 633 nm was used as a light source. Switching of light wavelength leads to changing of the Bragg's angle. According to (1), the Bragg's angle is θ = 17.4 ° (m = 1) at λ = 633 nm. Crystal samples with recorded Bragg gratings were placed on a rotating stage. Two photodetectors measured both zero-order and 1st diffraction order. Diffraction orders were measured by finding of maximal signal on photodetector by rotating the sample around θ = 17.4°. The rotating stage and photodetectors were connected to PC and can be managed automatically by a software program. Rotation of the sample allows us to measure angular selectivity shape (the diffraction efficiency dependences on the incident light angle). So using the theory of coupled waves [8] and comparing the measured angular selectivity shape of the hologram with the calculated one, it is possible thus to determine grating thickness (T) and refractive index modulation amplitude (Δn) in the direction of grating with high accuracy [3].

2.2 Method and equipment of Bragg gratings recording in germanate fiber

Optical scheme of the setup for Bragg gratings recording in germanate fiber (fiber Bragg grating (FBG)) is the same as shown on Figure 1 but there is germinate fiber sample instead of crystal sample. The sample is a special germanium-silicate anisotropic single-mode optical fiber with elliptical straining cladding [9]. The fiber is shown in Figure 3 (Figure 3A for a picture of the fiber and Figure 3B for a diagram of the fiber structure).

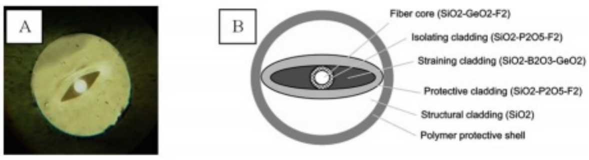

Figure 3. Germanium-silicate anisotropic single-mode optical fiber with elliptical straining cladding.
A – picture (face of cut section), B – structure diagram.

The diameter is 5 μm and 125 μm for the fiber core and structural cladding correspondingly. Such special structural design of the core and straining (stressing) cladding in particular allows to add anisotropic properties (birefringence) which maintain polarization of the light. These fibers are widely used in interferometric and other type of sensors with wide variety of applications [9]. The concentration of GeO2 in the fiber core was increased from the typical 4 mol.% up to 18 mol.% in order to increase photorefractiveness of the fiber. The polymer protective shell was removed from the fiber by a fiber stripper in the area of FBG recording which is about 40 mm in length. This exceeds the size of the recorded FBG length (L = 24 mm) in order to place the fiber closer to the phase mask (surface-to-surface).

Optical scheme of the setup for Bragg gratings measurement in FBG is shown on Figure 4.

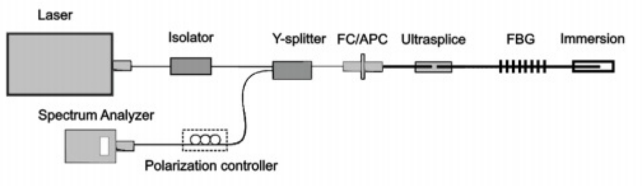

Figure 4. Optical scheme of the setup for Bragg gratings measurement in FBG.

This scheme is measuring the reflection signal of recorded FBG. The light source is narrowband THORLABS INTUN TL 1550-B laser with 1510-1620 nm tunable wavelength range and 0.005 nm step. Ultrasplice mechanical fiber connector with immersion is used to maintain a fast connection of fiber piece with recorded FBG to measurement scheme. Immersion on the other side of the fiber is used to eliminate Fresnel reflection and to measure only the signal reflected from the FBG. The signal from the laser distributes toward FBG through Y-splitter. Then it reflects from FBG toward Y-splitter. Non-reflected signal (if any) distributes further down to the immersion part and dissipates. Reflected part of the signal splits on the Y-splitter to about a 50:50 ratio: half of the signal decays by isolator and the rest of the signal goes through the polarization controller to the spectrum analyzer input. Since the fiber is anisotropic, polarization control is used to maintain the input of the signal into one of the selected axes of a birefringent optical fiber. Optical spectrum analyzer Hewlett-Packard 70951B with a measurement range of 600-1700 nm and a resolution of 0.1 nm is used as a light receiver. The experimentally established signal noise corresponds to a reflection of 0.01%, which makes it possible to register FBG with an accuracy of not less than 0.1%.

The method of FBG recording in optical fiber is the same as for LN crystal. But there are other fiber photorefractivity causes. Absorption of germanosilicate glasses has three maxima in the UV range of the spectrum located at 185, 242 and 325 nm [10]. There are several known and described mechanisms of photorefractivity in these types of fibers: electrooptical effect [11], electrostriction effect [12] and thermoelastic effect [13].

At long exposure times the induced modulation of the refractive index Δn becomes oversaturated, as a result of which the profile of periodic perturbations of the refractive index acquires a rectangular rather than sinusoidal shape [14]. Such a modulation of the rectangular waveform generates corresponding harmonic components, which, in accordance with the Bragg's law (1), gives a specific Bragg resonance in the spectral characteristic of the FBG. For example, according to [14], for $d = d_{pm} = 1065.3$ nm, effective refractive index $n_{eff} = 1.46$ and for the second resonance, the wavelength of the second Bragg resonance will be $\lambda = 1555.3$ nm. That is why it is fair to use a laser with a 1510-1620 nm tunable wavelength range in the scheme of the current setup for Bragg gratings measurement in FBG. For highly reflective FGB refractive index modulation amplitude Δn could be calculated by detecting and measuring the wavelength of Bragg's resonance λ, n_{eff}, and FWHM of Bragg reflection peak ($\Delta\lambda$) [15].

3. EXPERIMENTAL RESULTS

3.1 Experimental results of Bragg gratings recording in LN crystal

Bragg gratings were recorded in LN crystal in both single-pulse and multi-pulse sets. The results of the measurements of recorded structures with $\lambda = 633$ nm laser are shown in Table 1.

Table 1. Measurements of recorded Bragg gratings parameters in LN crystal.

Pulses amount	F = 180 mJ/cm^2	F = 660 mJ/cm^2
1	η = 0.50 % T = 4 μm $\Delta n = 1.9 \cdot 10^{-3}$	η = 1.55 % T = 7 μm $\Delta n = 3.37 \cdot 10^{-3}$
10	η = 0.80 % T = 5 μm $\Delta n = 2.46 \cdot 10^{-3}$	Above threshold
20	Above threshold	Above threshold

There was no evidence of hologram structure at laser fluence lower than F = 180 mJ/cm^2 which determines the minimal sensitivity level of laser fluence in the current optical setup. In a single-mode set the best parameters of the grating were achieved with F = 660 mJ/cm^2 laser fluence where diffraction efficiency is η = 1.55%. The measured angular selectivity shape of this grating shows that it has about $\Delta n = 3.37 \cdot 10^{-3}$ refractive index modulation amplitude and T = 7 μm thickness. In a multi-mode set, the best parameters of the grating were achieved with F = 180 mJ/cm^2 laser fluence and 10 laser pulses where diffraction efficiency is η = 0.80%, $\Delta n = 2.46 \cdot 10^{-3}$ and T = 5 μm. Exceeding a certain dosage of irradiation (threshold level) leads to local destruction of the sample. For example, it happens with 20 and more pulses with F = 180 mJ/cm^2 and with 10 and more pulses with F = 660 mJ/cm^2 laser fluence.

Figure 5 shows photos of recorded structures.

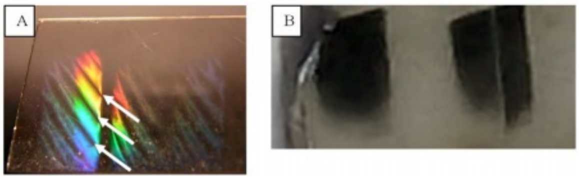

Figure 5. Photos of recorded structures in LN crystal.
A – structures recorded below threshold, B – structures recorded above threshold.

Figure 5A shows that structures recorded below the threshold have another collateral bigger period of grating (besides general grating giving full-colored diffraction) and it is shown with arrows. This relates to the optical wedge presence between the phase mask and the sample and the non-ideal contact of its surfaces. Figure 5B shows that structures recorded above the threshold have a dark color and severe absorption in the visible range.

Figure 6 shows pictures of recorded structures made with a TEM microscope.

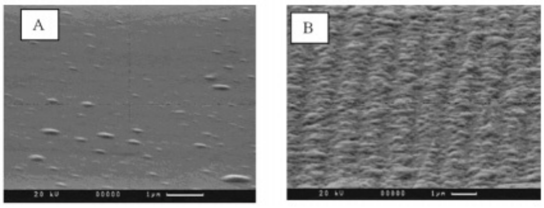

Figure 6. TEM picture of recorded structures in LN crystal.
A – structures recorded below threshold, B – structures recorded above threshold.

Figure 6A presumably shows local submicron areas with other than surrounding refractive index. Figure 6B shows surface grating with a period of about 1 μm. This period corresponds to the phase mask period.

3.2 Experimental results of Bragg gratings recording in germanate fiber

FBGs were recorded in germanate fiber in a single-pulse set. The results of measurements of recorded structures with different laser fluence is shown in Figure 7.

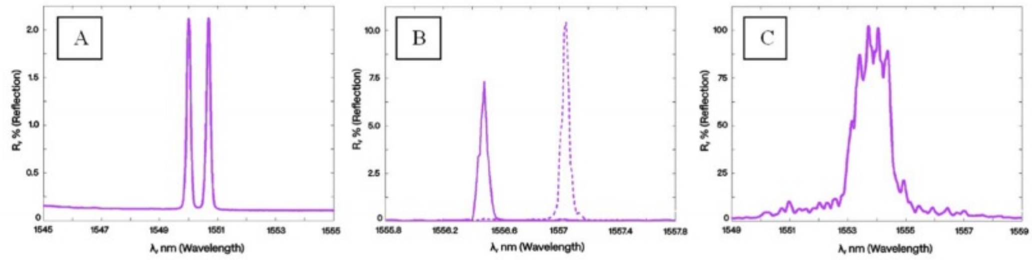

Figure 7. Measured reflection spectra of recorded FBG with different laser fluence.
A – F = 400 mJ/cm², B – F = 800 mJ/cm² and C – F = 950 mJ/cm².

Figure 7A shows the reflection spectra of the grating recorded by F = 400 mJ/cm² laser fluence. There are two reflection peaks at λ=1550.0 nm and at λ=1550.8 nm correspondingly related to each of the two orthogonal birefringence axes. The reflection is R ~ 2 % and the reflectance peak width is about 0.07 nm FWHM. There are minor insignificant changes in spectra when polarization is tuned by the polarization controller. Calculated n_{eff} = 1.4549 and n_{eff} = 1.4557 correspondingly for each of the two orthogonal birefringence axes. The calculated refractive index modulation amplitude is about $\Delta n = 0.11 \cdot 10^{-3}$. Figure 7B shows the reflection spectra of the grating recorded by F = 800 mJ/cm² laser fluence. Spectra are sensitive to polarization so there are spectral peaks related to each of two orthogonal birefringence axes that are independently brought to the maximum by the polarization controller (solid and dotted lines correspondingly shown on the compound graph). The spectral peak at λ = 1556.5 nm has reflection R = 7.1 % and 0.08 nm width (FWHM). The spectral peak at λ = 1557.2 nm has reflection R = 10.2 % and 0.09 nm width (FWHM). Calculated n_{eff} is 1.4611 and 1.4617 correspondingly. Calculated Δn is about $0.14 \cdot 10^{-3}$. Figure 7C shows reflection spectra of the grating recorded by F = 950 mJ/cm² laser pulse fluence which is close to a threshold level of germanium-silicate glass (~1 J/cm²). The spectral peak at λ=1553.8 nm has reflection R>99% and 1 nm width (FWHM). There are no dedicated spectral peaks related to each of the two orthogonal birefringence axes due to the great spectral width (FWHM) that overlaps corresponding peaks. Calculated n_{eff} = 1.4586 and $\Delta n = 1.9 \cdot 10^{-3}$.

Since the refractive index modulation amplitude of FBG recorded by F = 950 mJ/cm² is quite severe, it could be visualizated by microscope (Figure 8).

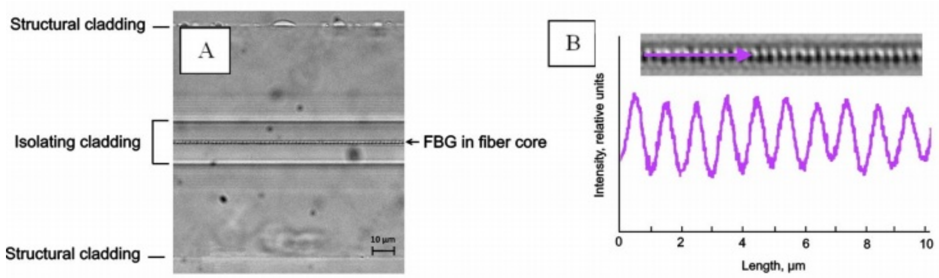

Figure 8. Picture of recorded by F = 950 mJ/cm² FBG.
A – photo from the microscope, B – grating period distribution along FBG vector (insertion above the graph – increased photo of FBG with an arrow showing computer processing axis direction).

Figure 8A shows a photo of the fiber made by optical microscope Zeiss Axio Imager Z1 with lens LD Plan-Neofluar 63×/0.75 Corr M27 using differential interference contrast method designed to visualize refractive index gradients. This FBG is clearly visible in the images, presumably because of the system of microcracks that is formed in the core of the fiber due to the thermoelastic effect [13]. Figure 8A clearly shows FBG recorded in fiber core with a diameter of 5 µm, isolating cladding with a diameter of about 20 µm and structural cladding with a diameter of 125 µm. FBG is situated whether right inside the fiber core or on the border between the core and isolating cladding that allows it to interact with the signal passing through the fiber core. Figure 8B shows the grating period distribution along FBG vector making by computer processing of the photo shown on Figure 8A. The insertion above the graph shows the computer processing axis direction. It is clear that the FGB period is about d = 1 µm and matches the period of phase mask d_{pm}. Other recorded FBGs with much lower Δn cannot be visualized this way due to limited contrast and resolution.

4. CONCLUSION

Bragg gratings in the present optical setup are more suitable to be used in integral and fiber optics, the principal possibility of recorded holographic gratings with induced refractive index modulation shown here might open other applications including hologram recording in this crystal and glass for AR/VR/XR applications. It is shown that induced refractive index modulation achieved in the current setup is $\Delta n = 3.37\cdot10^{-3}$ (at $\lambda = 633$ nm) for LN and $\Delta n = 1.9\cdot10^{-3}$ (at $\lambda = 1550$ nm) for germanate glass.

It should be noted that Bragg gratings recorded in LN crystal lose their diffraction efficiency over time and eventually dissipate in about one month at room temperature. One way of fixing these gratings is when the crystal is specially doped in order to record ion grating rather than electron grating [5].

A simple optical setup of recording volume phase gratings in LN crystal and in germanate fiber using an excimer nanosecond UV laser and phase mask was proposed. It could be modified, for example, by adding reflecting mirrors behind the phase mask (or behind beamsplitter) in order to have the possibility to maintain and change the angle of light incidence on the sample in both channels.

It is required to study further other possible single-pulse and multi-pulse sets with other parameters of laser fluence and amount of pulses for both LN crystal and germanate glass. The process of Bragg gratings recording in germinate glass bulk should be similar to one in germinate fiber, but it needs to be studied and explored further.

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Exploring angle-dependent image sharpness in reconstructed augmented reality image with holographic waveguide display

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ABSTRACT

Increasing interest in the metaverse world these days, interest in realistic content such as 3D displays is growing. In particular, hologram images seen in movies provide viewers with an immersive display that cannot be seen in conventional 2D images. Since the first discovery of holography by Dennis Gabor in 1948, this technology has developed rapidly. Spatially, this beginning of technology like Optical hologram called analog hologram and Digital hologram such as computer-generated hologram (CGH). In analog and digital holograms, a recording angle and a recording wavelength are having important role when reproducing and display hologram. In the hologram, diffraction of light causes by unexpected formed by the synthesis from interference with object and reference light. When recording, the incident light information and mismatched reproduction light reconstruct the hologram in an undesirable direction. Reproduction light that is out of sync with incident light information with initial condition of recording will cause reconstructed image in an undesirable direction. Therefore, we analyze the holographic interference pattern generated by hologram recording in volume holograms using photopolymer and analyze the characteristics that vary depending on the angle of the reproduced light. This is expected to be used as a basic research on various holographic application that may cause as holograms are applied to industries in the future.

Keywords: Hologram, Photopolymer, Volumetric Hologram, Angular Selectivity, Hologram Reconstruction

1. INTRODUCTION

Current holography technology requires a medium capable of recording holographic interference patterns for reproduction. We call this a holographic medium or holographic film for convenience. A holographic medium records all information of an object in the form of an interference pattern on a photosensitive material in the form of a thin film. The holographic medium is recorded as a one-off and produced semi-permanently. Representatively used media include silver-halide photopolymer, dichromatic gelatin, and photoresist. The essential elements of the medium used for holography are as follows. High-resolution pattern recording must be possible on a medium, and a constant spatial frequency response is required. In addition, since it has a wide spectrum, it should be possible to record colors in various wavelength bands [1-3]. In addition, since the nanoscale interference pattern is recorded as a pattern, it should have high sensitivity and response speed because the quality is deteriorated even with small vibrations. As an element for realizing an environment suitable for workers, it is good if the development is simple and unnecessary, and it is good if non-polluting chemicals can be used. In addition, for mass production or commercialization, it is good if the medium is easy to supply and demand. Silver salt emulsion is the most sensitive material among holographic media and is developed with very high resolution [4]. This is expressed using a measure of image brightness called diffraction efficiency, and has a value of over 90% at its maximum. Silver salt emulsion can produce high-sensitivity holograms, but it is difficult to develop and sensitive to humidity and temperature, so holograms can be damaged if they are not produced and stored in a 100% good environment. In addition, since all systems currently do not produce media through automation, uniform characteristics of the media used cannot be guaranteed [5]. Therefore, when producing a hologram, it is always necessary to test the efficiency and reactivity of the medium before proceeding. This acts as a major obstacle in mass production of uniform products. This problem can be solved by using a photopolymer. Since the photopolymer also has a high diffraction efficiency of 90% or more, the silver salt emulsion can reproduce a display with the same sensitivity. In addition, unlike silver salt emulsions using dichromate gelatin, it shows advantages in terms of temperature and moisture. Due to these advantages, it is widely used in fields such as optical devices and security for displays, and is attracting attention as a material for mass reproduction of full-color holograms [6,7]. In this study, while recording holograms on a volumetric holographic medium using photopolymer, we propose an analysis method for the angular characteristics that change when restoring object light using reproduction light by analyzing the form of grids. The analysis result of this study is an analysis of the hologram reproduction environment recorded and reproduced in a volumetric hologram such as photopolymer, and it can be used as a guide for analyzing the optimal environment to restore the image of a hologram produced in the future.

2. BACKGROUND THEORY

2.1. Hologram recording and reconstruction

Figure 1 shows the process of recording and reproducing a hologram. The light emitted from the laser is divided into two through a beam splitter, and one is used as a reference light that shines on the holographic medium as it is, and the other is used as an object light to reflect object information and transmit it to the medium. Both lights travel in the form of a uniform spherical wave after the light emitted from the laser is diffused through the objective lens. In this process, since no lens is used to create an image of an object, holography is also called lensless photography technology. When the object is viewed as an aggregate of all point sources, the holographic interference pattern created in this way includes an amplitude, which is information about brightness, and a phase, which indicates information about direction, in each point source. In order to reproduce a 3D image in a hologram, the technology to record and restore this phase information is the key [8-10]. This phase information interferes with the direction information of the object we know and the standard light called reference light, and the phase difference is recorded on the holographic medium. In this case, if only the reference light is illuminated at the same angle after the recording is completed, the phase difference as well as the amplitude information is restored and the object is reproduced in its original position [11].

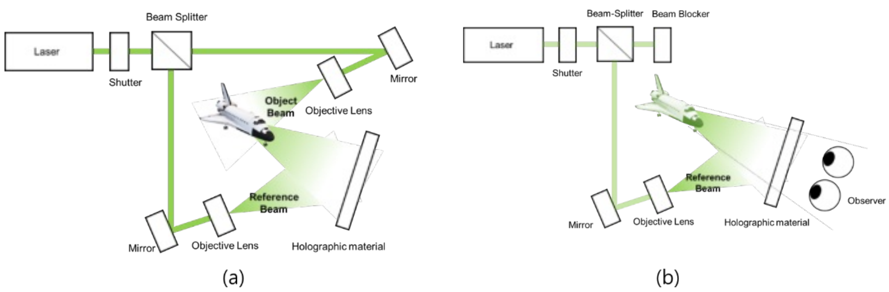


Figure 1. (a) Hologram Recording (b) Hologram Reconstruction

2.2. Holographic interference pattern

A hologram starts from interfering reference light and object light with each other. When the part with the largest amplitude, that is, the part with the highest wave, meets each other, it is amplified, and when the part with the highest amplitude and the lowest part meet, they are canceled. A pattern of light and dark is formed in space from the intensity of a point light source coming from an object. This interference pattern changes from the relationship of the relative positions of the two light sources [12]. Figure 2 shows the shape of the holographic interference pattern.

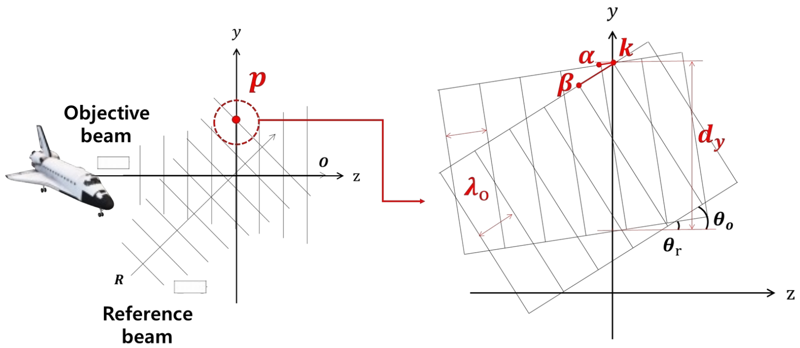


Figure 2. Pattern for interference of two plane waves

If both waves are regarded as plane waves for simplicity and intuitive understanding of the equation, if the reference light and the object light are incident at point p on the hologram surface, the angles of incidence are θ_r and θ_o with respect to the axis, respectively, and the wavelength is λ_o. if the amplitudes of both lights are maximum at point p, we say that the phases are the same. The result of interference at this location is the formation of a bright fringe. If q is the position on the x-axis that becomes brighter next, the object light and the reference light are shifted by one wavelength at this position. Therefore, the distance between p and q becomes the pattern spacing in the x-axis direction, and if this is denoted as d_y, the following equation (1) is established [13].

$$\alpha k - \beta k = d_y(\sin\theta_r - \sin\theta_o) = \lambda_o \qquad (1)$$

At points below p, the value of $\sin\theta_r - \sin\theta_o$ increases. Therefore, if the wavelength is constant, d_y becomes smaller and the pattern becomes more detailed. This is the reason why patterns with different intervals and directions are formed depending on the position of the hologram face. If the position of R or O is changed, the interference pattern changes. When an object has a three-dimensional shape, object light overlaps light emitted from each point from the surface. In addition, since a complex wavefront is formed instead of a simple spherical wave, it is difficult to record the same hologram if there is no object used for recording or if the location is slightly different. In the case of photopolymer, it is a medium that is 6 to 7 times thicker than silver salt emulsion [14]. If so, it is necessary to analyze the characteristics of these spacings and directions in more detail. When recording a reflective hologram to realize an environment that can be viewed by an observer, the condition of the reference light must be incident with a waveform of the same wavelength and position during recording [15]. Otherwise, the observer may experience inconvenience in having to use different angles or different wavelengths of illumination. In addition, photopolymer has a great advantage as a translucent screen because it blocks diffraction of external noise light due to its narrow reproduction spectrum, but if accurate reproduction is not performed, irregular modulation in which the angle and wavelength are shifted may occur.

3. METHODOLOGY

3.1 Numerical analysis of reconstruction images

Assuming that R is a divergent spherical wave, a (+) sign is used, and if it is a converging light, a (-) sign is used. Calculate hologram can be said to be the set of all point sources emanating from an object. Equation (2) below is an equation for calculating the restoration point of the reproduced image numerically through the lens equation [16].

$$1/(1/R_o - 1/R_r) = (R_o R_r)/(R_r - R_o) \quad (2)$$

Through this, it can be confirmed as shown in Figure 3 how the image changes according to the position of the playback lighting source. Figure 3(a) shows the process of recording a hologram using a light source, and Figure 3(b) shows that the playback position changes when the light source is changed. The analysis in this study will use two parallel beams with a diameter of 1 cm. The reason is that most measuring devices that measure the amount of light have a sensor size of $1cm^2$, so it is easy to measure. In this paper, we experiment and analyze how the diffracted restored light changes the playback position by using the playback light that slightly deviate from the angle at which the hologram was initially recorded as above.

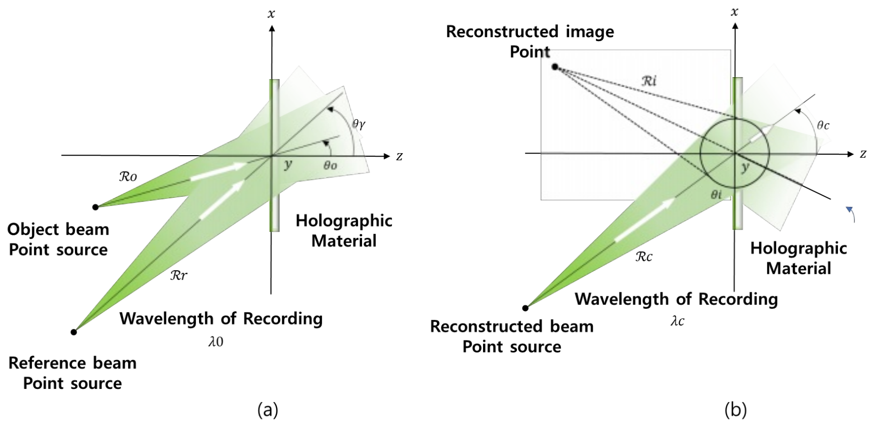


Figure 3. (a) Hologram Recording with point source (b) Hologram Reconstruction with point source

3.2. Optical system configuration

Figure 4 shows the optical setup configured for the experiment.

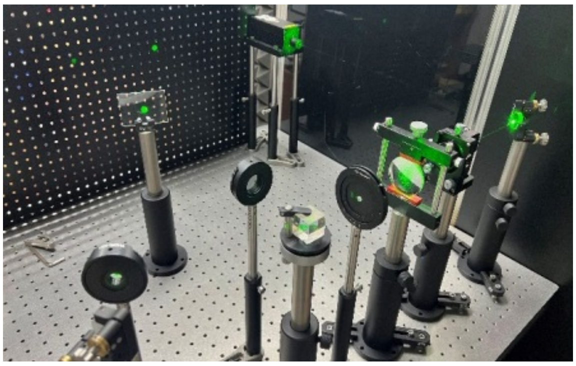
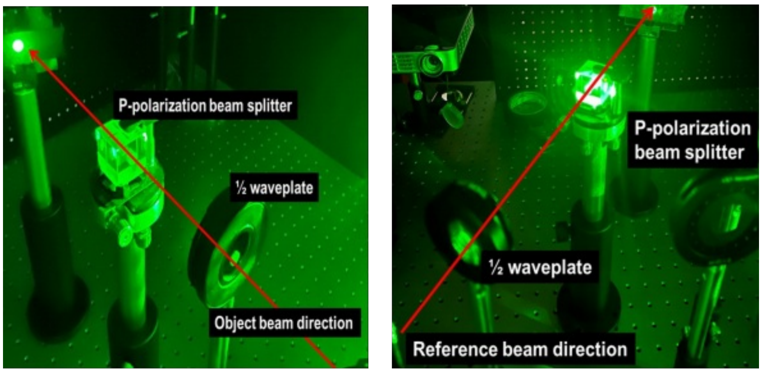


Figure 4. Photopolymer recording system setup

Light from a green laser with a wavelength of 532 nm is refracted by 90 degrees after passing through the first mirror. This beam passes through a collimation lens after passing through a spatial filter to filter noise components and then being diffused. The collimated beam is divided into two object beams and reference beams through a beam splitter. In this process, it passes through various optical components such as beam splitters, mirrors, lenses, and filters. Since most of the systems are implemented by hand by optical designers, it cannot be guaranteed that the angle of reflection is completely inconsistent with the design. Therefore, in order to maximally match the polarization of the two beams recorded on the final hologram surface, as shown in Figure 5, the P-polarization beam splitter is placed in front of the wave plate and the power of the object light and reference light is adjusted so that the maximum amount of light is output.



(a) (b)

Figure 5. Polarization matching on recording plane
(a) Object beam direction (b) Reference beam direction

Fig. 5(a) shows the setup to match the polarization in the object light direction and Fig. 5(b) the polarization in the reference light direction. Since the P-polarized beam splitter passes only the P-polarized wave, even if it is not precisely matched with linear polarization, the direction of polarized light can be matched on the recording surface, enabling high-efficiency hologram recording.

4. RESULTS AND DISCUSSION

4.1. Efficiency changes according to the playback light angle

Figure 6 shows the optical configuration for measuring the efficiency depending on the angle with the playback after recording the hologram.

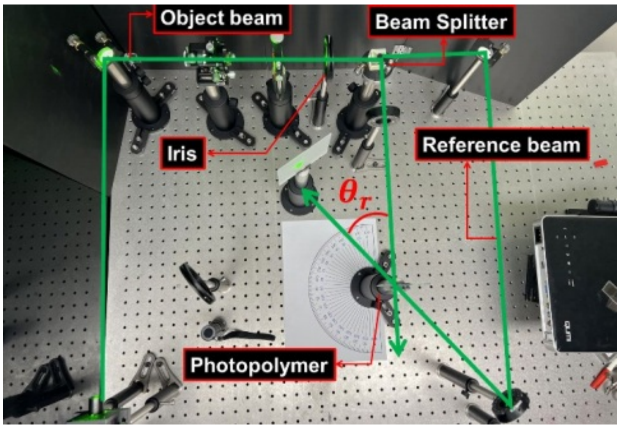


Figure 6. Efficiency analysis according to the reference light angle optical composition after hologram recording

The output of the laser was set to an output of 100mW. The laser light thus oscillated is refracted at 90 degrees through the mirror. The refracted light passes through a spatial filter and passes through a collimation lens having a focal length of 100 mm to produce parallel light. Here, for the convenience of measuring the amount of light, as previously described, a circular collimated light having a diameter of 1 cm is made using an aperture and introduced into the beam splitter. Among the beams divided into two optical paths from the beam splitter, the light vertically incident on the photopolymer was set as the object light, and the light propagated to the remaining path through the medium at an angle of θ_r passing through the medium through the two mirrors was set as the reference light. The θ_r value is scheduled to be recorded at 40 degrees, and using a marker that can indicate the angle under the medium with this reference angle as the center, the playback light is changed at angles of 30 degrees, 35 degrees, 40 degrees, 45 degrees, and 50 degrees. conducted an experiment. The light quantity ratio of the reference light and the object light is 1:1, and exposure is performed with a total light quantity of 4mW, each 2mW on the medium side. Figure 7 shows the result of the change in efficiency according to the angle of the playback light. Fig. 9(a) shows the result of the regenerated diffraction beam, and Fig. 7(b) shows the intensity of the regenerated light at a standardized level as a graph. Due to the nature of the photopolymer, exposure above a certain saturation range is sufficient. If you look at the photopolymer data sheet, it says that 20mJ of energy per cubic centimeter is required, so a 10-second exposure is sufficient, but for convenience, a recording time of 30 seconds was used. 30degree, 35degree, 40degree, 45degree, 60degree light intensity and diffraction efficiency of the reproduced image of the restored image using the reproduced light, and the restored image is extracted as 2D data, standardized to 255 levels, and converted into gray scale as shown in Figure 7. showed up This is the result of using the same amount of light, 2mW, to irradiate the medium with the reference light during recording, but using different angles of the reproduction light with θ_c

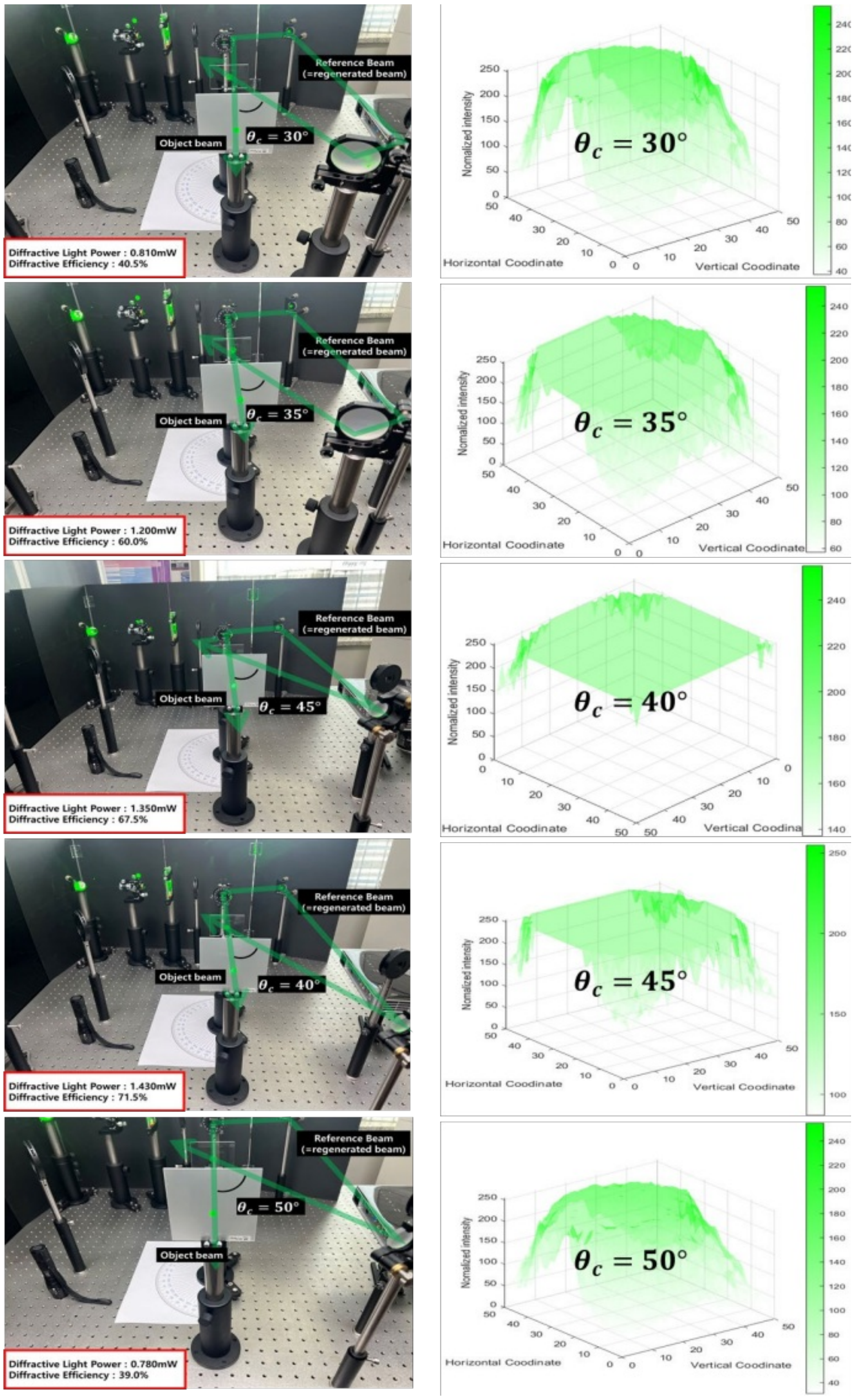


Figure 7. (a) Reconstructed diffraction beam results for each angle
(b) Normalized intensity simulation results for each angle

After recording at a recording angle of 40 degrees, irradiation at a reproduction light angle of 40 degrees shows an efficiency of 71.5%. Theoretically, the current recording system shows the highest efficiency, and it can be seen that the efficiency decreases whenever the angle changes. At a reproduction angle of 30 degrees, the reproduction light intensity was 0.81mW, and the efficiency was 40.5%. At a reproduction angle of 35 degrees, the reproduction light intensity was 1.20mW, and the efficiency was 60.0%. At a reproduction angle of 45 degrees, the reproduction light intensity was 1.35mW, and the efficiency was 67.5%. At a reproduction angle of 50 degrees, the reproduction light intensity was 0.78mW, and the efficiency was 39.0%.

2. Analysis of restoration for each angle according to the distance of playback light

Figure 8 shows the result of analysis of the reconstructed image, which differs in the case of parallel light and spherical wave emanating from a point light source.

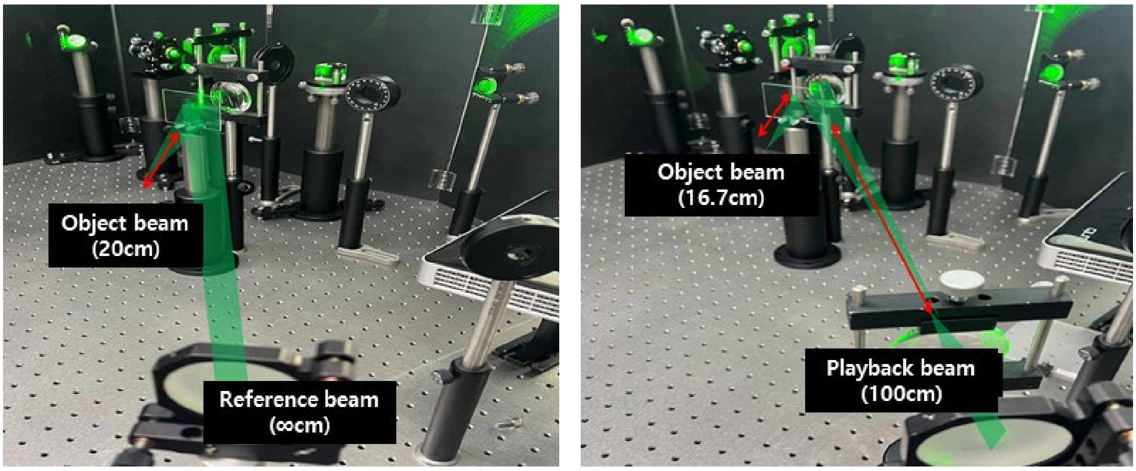


Figure 8. (a) Hologram recording using plane wave
(b) Hologram reconstruction using distance of 100cm light

Based on the reflective hologram recording method, the reference light recorded was an infinite distance, that is, parallel light, and the recording angle was 45 degrees. As shown in Fig. 8(a), the object light converged on the holographic medium at 100mm in front of the beam splitter by using a convex lens with a focal length of 300mm in front of the beam splitter. In this way, it becomes a hologram in which light converges at a focal distance of 20 cm from the medium. Figure 8(b) shows the changed position of the converging light according to the distance of the hologram reproduction light. The reproduction illumination light was incident on the hologram by using a point light source of 100 cm as the reproduction light, unlike the parallel light of infinite distance at the time of recording. At this time, the restored hologram showed a restored image in which light converged in the form of focusing at a position of 16.7 cm. This proves the numerical analysis of Equation (2) below at which position the replayed image is restored.

6. CONCLUSION

We analyzed the recording characteristics of a volumetric hologram using photopolymer as a medium and conducted a study on the angle using reproduction light. In particular, the efficiency varies depending on the recording angle and playback angle of the hologram, and to compensate for this later, a research method for the values to be analyzed in advance was proposed, and reliability was demonstrated through experiments. Looking at the recent trends in hologram research, photopolymers are being used more often than silver salt media. The reason is simple. The silver salt medium reacts sensitively to the exposure energy. Therefore, it is not only difficult to record, but also requires a separate wet post-processing process after recording. The bleaching and developing process must also follow the exact time and process. However, in the case of a photopolymer, since a monomer chemical reaction is used for photosensitization, even if energy is applied over a certain period of time, the hologram is not damaged or the efficiency is not rapidly lowered due to overexposure. We use various light sources to reproduce the hologram after recording. I observe holograms in natural light under the sun, and I try to observe holograms by adjusting the angle well under general building lighting. The most accurate thing is to reproduce it by matching the exact wavelength, recording angle, and reproduction distance at the time of recording, but it is too difficult for the general public who are not familiar with holograms. Therefore, the research on angular characteristics in this paper is thought to be available as a research material that can analyze angular characteristics from more diverse perspectives to the public who experience holograms or to scientists researching related fields in the future. This is applied to the field of realistic content reproduction such as holographic optical element (HOE), holographic HUD (Head-Up Display), holographic HMD (Head-Mounted Display), etc. I hope that the industrial development of holograms will continue in the future.

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TRACK 6.

Technical Applications

A large-scale pulse laser holography camera built with 3D printing and surplus optics

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ABSTRACT

A collaboration between artists and researchers brought about a new holography facility at the University Gallery in Newcastle, Australia. With the donation of a Geola G10J – TWIN pulse laser via the Center for the Holographic Arts the team sought to make an adaptable pulse laser holography camera. The system was built with surplus optics and using a modular frame. 3D-printed parts were designed to enable a highly adaptable configuration.

Keywords: Pulse laser, 3D printing, holography, studio

1. A PATH OF PROJECTS

For a large-scale holography project in 2009 Dr. Paula Dawson commissioned Geola to create a powerful pulse laser, capable of recording large volumes. While the project never occurred, the laser made it to Australia. In 2018 Dr. Martina Mrongovius arranged for the laser to be transferred from the University of New South Wales to the Center for the Holographic Arts to enable artist projects in Australia and then brought the laser to Melbourne for a project with the artist Julia deVille.

1.1 Unboxing a pulse laser

Mrongovius introduced the artist Julia deVille to making holograms at RMIT University in 2016. They then made a series of holograms of her jewellery and bejewelled taxidermy creatures on the floor of a yoga studio in 2017. For deVille's exhibition "Wholeness and the Implicit Order," at Linden New Art in 2018 the artist wanted to create large holograms. Mrongovius worked with deVille to digitally record an Alpaca rocking horse and then print a limited edition of holograms with Dr. John Perry at Holographic North [Fig.1].

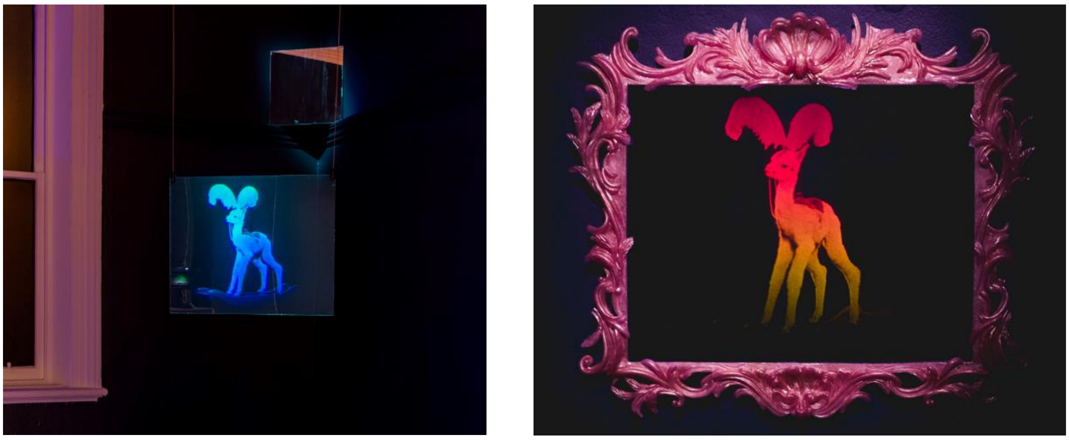


Figure 1. Alpaca multiplex transmission holograms, illuminated with filtered light. Left, the track light illumination is bounced off a wall mounted mirror. Right, the hologram is framed with a mirror backing and illuminated with two lights with pink filters to extend the vertical field of view. Julia deVille, "Wholeness and the Implicit Order" exhibition at Linden New Art, Bunurong Boon Wurrung Country, 26 Acland Street, St Kilda Vic 3182 Australia. 25 August - 4 November 2018
https://www.lindenarts.org/exhibitions/linden-new-art/julia-deville/

For the deVille' taxidermy zebra and baby giraffe the plan was to record large laser-viewable transmission holograms using the pulse laser. A warehouse was made available and Mrongovius began sourcing the optics that would be needed. With the laser producing a 16mm diameter beam, 2" diameter optics (50.8mm) were chosen and sourced from Sterling Resale Optics along with optical mounts from eBay.

On arrival to Australia with a suitcase packed with film, developing trays and optics, it became clear that the project was running behind schedule and the zebra and baby giraffe may not be ready in time to be made into holograms. It was decided to instead create a series of holograms of the smaller bejewelled creatures and so chemicals were ordered and the unboxing of the laser begun.

Figure 2. Assembling of the laser umbilical cords and connections at the warehouse in Collingwood, Australia.

1.2 A twist in the plot

The laser was set-up and the pilot beam was used to begin the camera alignment. The chemicals however had not arrived. They had been rejected by the shipping company and no other supplier could deliver what was needed in time. Mrongovius had been working with the Bayer HX photopolymer in New York so arranged for express delivery of a few packets of film and set up a table in the office of the warehouse with 150mW Coherent sapphire laser, a thick piece of laminated timber and set of Vespa innertube tires. The holograms produced included laser-viewable transmission holograms and reflection holograms. The laser-viewable holograms were illuminated by a blue laser diode, the beam was spilt and then expanded by two concave mirrors to provide illumination for two artworks in the exhibition.

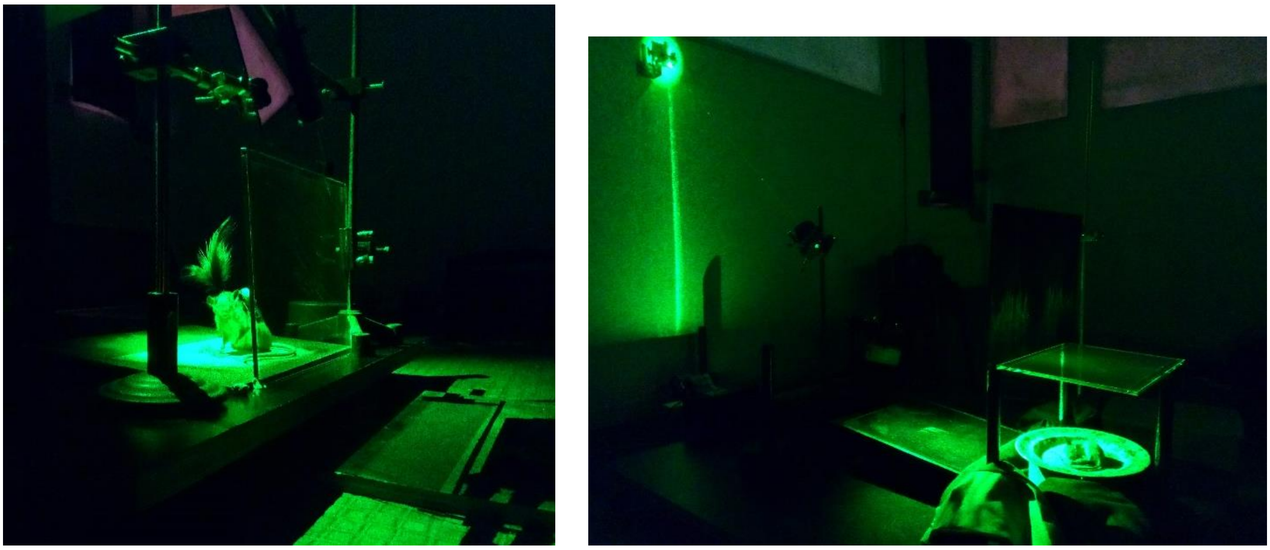


Figure 3. Single beam laser viewable set-ups for recording with photopolymer. The darkening shadow of the film was used to judge exposure, with exposure times of up to 6 mins.

1.3 Another project

On a visit to Australia in 2020 that turned into relocation Mrongovius met with another high- profile artists who wanted to explore large scale holography and so began again to look for a team and studio.

2. A NEW COLLABORATION

On joining Lake Macquarie City Council to develop the Lake Arts Precinct in Australia, Mrongovius reached out to the local physics department and was delighted to connect with Associate Professor John Holdsworth who had provided technical support to Paula Dawson to create the triptych *To Absent Friends* at the Acoustic Laboratory in the mid 1980's. More recently he had provided technical support for Newcastle Art Gallery's exhibition *VIRTUAL ENCOUNTERS Paula Dawson Holograms* in 2010.

Holdsworth worked in industry for 12 years, including three years with Spectra-Physics working on lasers before returning to academia to pursue a PhD. His research includes the development of laser ranging (LiDAR) systems. Holdsworth established the Photonics bachelor and honours degree programs at the University of Newcastle and served as Secretary of the Australian Optical Society for 10 years.

Matthew Willis joined the pulse laser holography team after meeting Mrongovius at an augmented reality workshop at the Multi-Arts Pavilion *mima* – a venue for digital and performing arts in Lake Macquarie.

Willis, a University of Newcastle alumnus, had studied under Holdsworth's supervision until 2017. His path shifted from physics into the technical arts with an artistic practice that is oriented by optical physics. Willis creates numerical controlled machines for the creation of specular holograms. He is currently developing a new kind of direct-write digital hologram printer. Willis intends to produce computer-generated models for his own visual arts practice as well as providing opportunities for Australian artists. Studying holographic optical elements, and computer graphics to form digital holography, Willis's artistic practice aims to advance holographic principals through multi-dimensional visual storytelling. In addition to creative projects Willis provides consultancy for technical creative spaces.

Willis has previous laser experience characterising a Titanium-Sapphire Q-switched system building and analysing a frequency resolved optical gate (FROG). He has also produced technical models for 3D printing, this became a valuable and cost-effective solution for mounting optical hardware onto the Ezy-strut framing system used in this project.

The University Gallery, at the University of Newcastle Callaghan Campus offered the Pulse Laser Holography Project two adjoining studios to house both the laser and holography camera.

3. THE G10J – TWIN PULSE LASER

3.1 Twin head pulse

Figure 4. G10J – TWIN pulse laser with control cabinets shown on right. Supplied by Geola

The powerful pulse generated by the G10J laser head is achieved by a topological master-oscillator that is then split into two channels, each being amplified and compressed through two more additional stages with each channel generating a mutually coherent (maximum 5 Joule), 30 nanosecond pulse at 526.5 nm.

3.2 Alignment

Unpacking a laser that has been in storage for years and moved to various locations we first visually inspected all optics for signs of damage, including degradation of coatings or accumulation of dust, mould or cobwebs.

To analyse the beam profile, we used exposed and developed photopaper to create 'burn patterns' recording the high energy 1052nm deep infra-red pulse throughout the beam path. When exposing the photopaper it is placed within a plastic bag, or covered by sticky tape, so as to contain and protect the optics from the ablated emulsion. The other tools we use are laser diodes for alignment and a dentist mirror to inspect optics. Each stage of the lasers amplification increases the beam diameter by means of telescope's starting from 5mm increasing to a larger 16mm FWHM collimated beam at the output aperture.

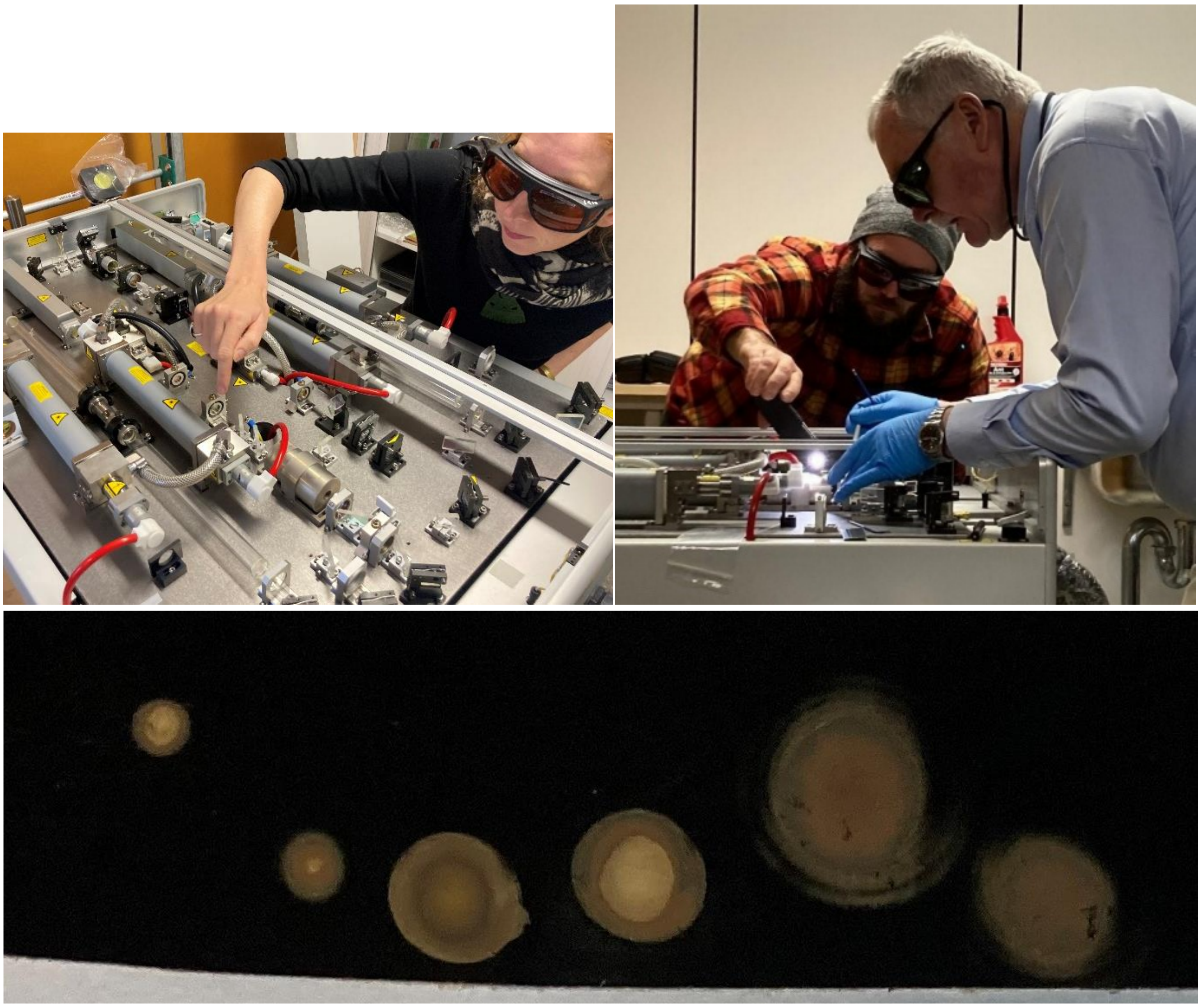


Figure 5. Above: Aligning the laser and checking optics. Below: a series of burn patterns on photopaper. From left to right; exit from master oscillator, entry into preamplifier, exit from preamplifier, telescope lens 1, telescope lens 2, exit from faraday rotator.

Becoming an expert on a new laser system takes time and consideration, to understand and to some extent control the physics involved in the beam formation. The physics involved includes spatial, temporal and thermal effects that all work in concert to achieve the optimal beam profile. As a commercial system there is dedicated electronic control over temperature for second harmonic generation, precise electrical timing system for firing pump lamps and a water-cooling system for the gain stages. However, skilled operators are still required to ensure that the optics are precisely co-linear to the optical axis.

High energy systems like the G10J require optical path lengths in the order of several meters, so delay lines are made by folding the beam path between optical elements and lasing media. Back reflections need to be minimised while the system also requires precise alignment with the optical axis of each stage. Therefore, checking the beam path at many points of interest within the system is necessary to achieve a high-quality pulse at the output.

Over many iterations, the alignment converges as close as possible to these axes. Fine adjustments are made with conscious and deliberate movements. The down-stream path is highly dependent on the upstream quality, so any unwanted effects will be amplified during each stage. This can make the alignment procedure an arduous task.

While we have now inevitably become experts in the operation of the Geola G10J we have not been entirely successful. Our G10J was first commissioned over a decade ago in 2009 and unfortunately the anti-reflection coating of one of the gain stages is damaged. This will require replacement of the laser rod amplifier in order to restore the system to full working order. Being a twin-channel pulse we are still able create recordings with one channel, by blocking the damaged channel and turning of the amplifiers until the repaired is made.

4. THE CAMERA

4.1 Compact design

While the laser is capable of recording very large volumes, the studios offered by the University Gallery are tight ~ 4x6 m rooms. To optimise the space available and separate the talent/art-making from the Class IV laser we put the laser in one studio and then removed the upper wall panels for the beam to pass through. With this arrangement we have created an imaging area of approximately $1.5m^3$

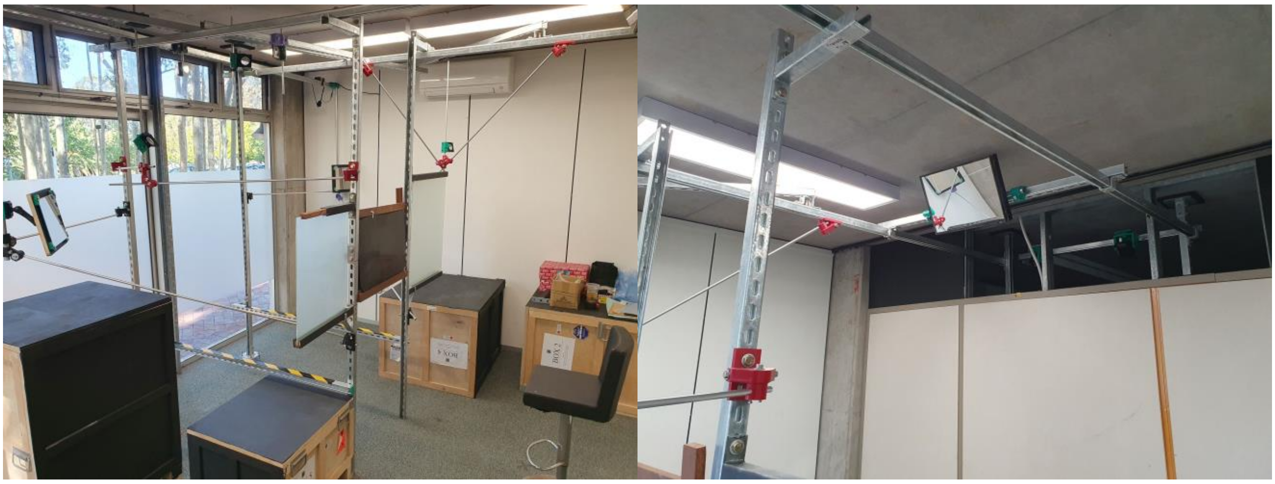


Figure 6. Left: Camera studio showing the overhead framing system, 3D Printed optical mounts holding posts for mirrors and lenses, supporting struts and two diffusers either side of a black glass plate for the temporary lamination of the film. Right: overhead rails passing through the adjoining wall, reference mirror and printed support struts.

4.2 Supporting structure

We decided to construct a free-standing frame for all the optics using the Australian made Uni-Strut/Ezy-Strut channel system. This system was chosen as it is readily available, cost effective, ridged and reconfigurable. Our core design was based around two-beam illumination of the subject and an overhead reference beam. The overhead truss system runs between the two adjacent rooms.

Figure 7 shows the camera frame with the two long horizontal struts held aloft by four vertical struts. The verticals are clamped between the floors and ceiling, two additional verticals are used to secure the diffuser and recording plate to the frame. Crossbars provide points for fixing the optical post mounts. Additional supporting struts constructed from 12mm aluminium tube are used to fix the post mounts to provide stability where needed.

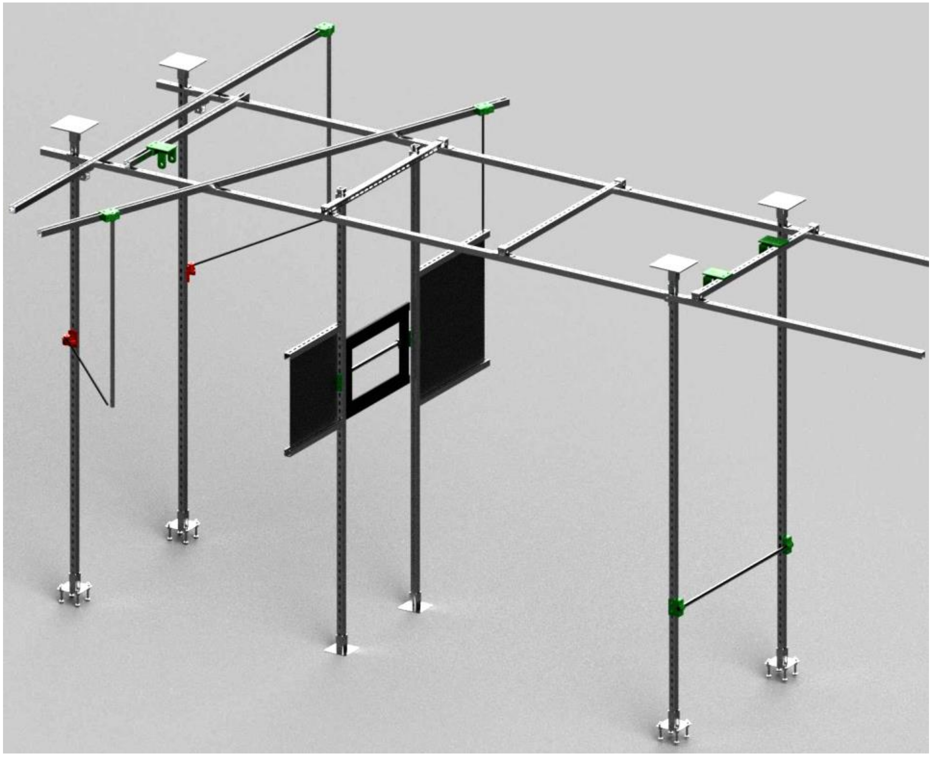


Figure 7. A computer generated render of the support structure. (Separating wall not pictured)

Matching the paths lengths from laser exit to recording plate is important to ensure temporal coherence. To do this we first sketched the system, and marked out mirror positions on the floor. Once the optics were in place we performed trial and error iteration using paracord, first matching the left side from the beam-splitter through the left object illumination and reference beam to the plate. The right-side object beam illumination was then matched to these paths. Considering the volume recorded, our aim was to match path lengths to within 10mm with an object volume centred 500mm in front of the recording plate.

This camera arrangement illuminates the object with a tighter beam through the left ground-glass diffuser and a broader beam through the right-side diffuser. Adjusting the power of the right channel, or changing the distance to the object beam expansion lenses enables artistic control of the scene lighting. The reference beam could also be expanded further to back-light the scene.

4.3 3D printing to connect optics to the Ezy-strut

All of the 3D printed parts were designed with compatibility for optical system standards by using cap-head hex bolts and standard optics post diameters of 12mm 25mm and 38mm. Adjustable axes with rotation around a supported post were made by allowing the tensioning of a single, or pairs of, cap-head bolts to the printed parts. These rotational stages use a conical bearing and clamp mechanism as seen in in Figure 8.

The 3D models were printed with a Prusa i3 clone; using a 0.4mm nozzle, 1.75mm filament, Polyethylene terephthalate glycol (PETG) thermoplastic. The material was fused at a temperature of 250℃ at a 0.2mm layer height. The bed temperature was set to 60℃ and the printer was operated in an open room at ambient temperature. The models were sliced using the Prusa-slicer with infill set to 100%. Parts weighed between 100 and 400g after incorporating captive locking nuts where needed.

These parts were designed to cover the additional adjustability required for the 2″ optics to relay and expand the beam from the overhead path down to the diffusers and to the recording plate via the expanding lenses and folding mirrors.

For the two 200 x 250mm object beam mirrors, off the shelf adjustable speaker arms were used. These were chosen as they have extended and articulated joints that allow for a wide range of positioning. The two object beam mirrors are attached to wooden boards mounted on the speaker arms and are held in place by 3D printed stand-offs with a magnetic catch.

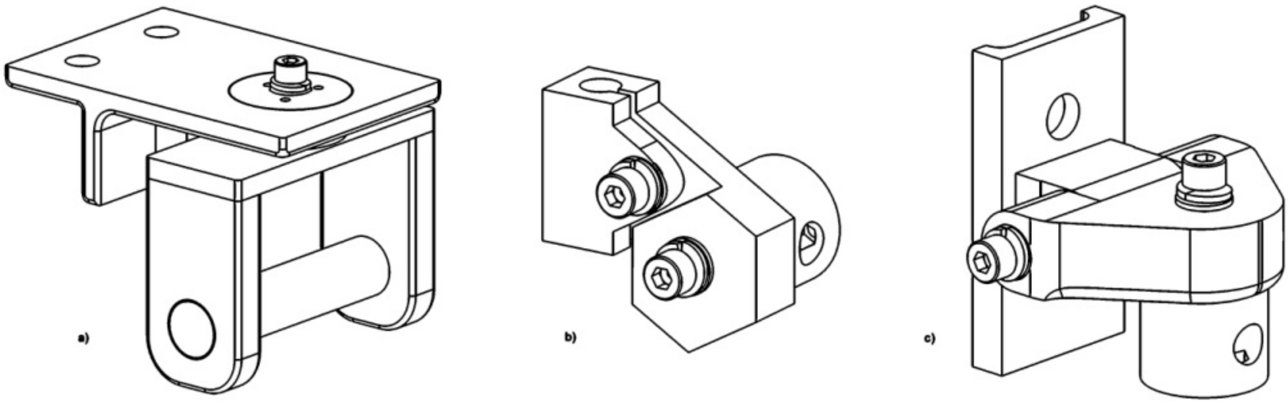


Figure 8. a) Large 2″ optical mount rotational bracket for mounting to Ezy-strut framing system b) 25mm to 12mm standard strut support used to guide support struts c) accompanying frame supports.

4.4 Class-IV laser system safety requirements

Australia adopts the laser safety standards described in AS/NZS IEC 60825.1,14 which outlines the maximum permissible exposure to laser light as well as safety requirement for laser systems and products. These standards include details for when environment control must be used in addition to the safe exposure limits. The G10J amplifier settings allows for control of the output energy level.

Best practices including beam blocks around components and barriers to prevent access to unsafe emission have been implemented at the studio. To meet the University of Newcastle’s safety requirements a door interlock is maintained to prevent walk-in access to the room while the laser is operating.

Thorlabs provided the necessary safety glasses for working with the laser system while tuning the beam’s path. We use two types of glasses. The LG10 blocks both the 1052nm and 526.5 nm lines and is used when tuning the lasers master oscillator and amplifiers. The LG1 blocks only the 1052nm line allowing alignment of the beam pilot through camera.

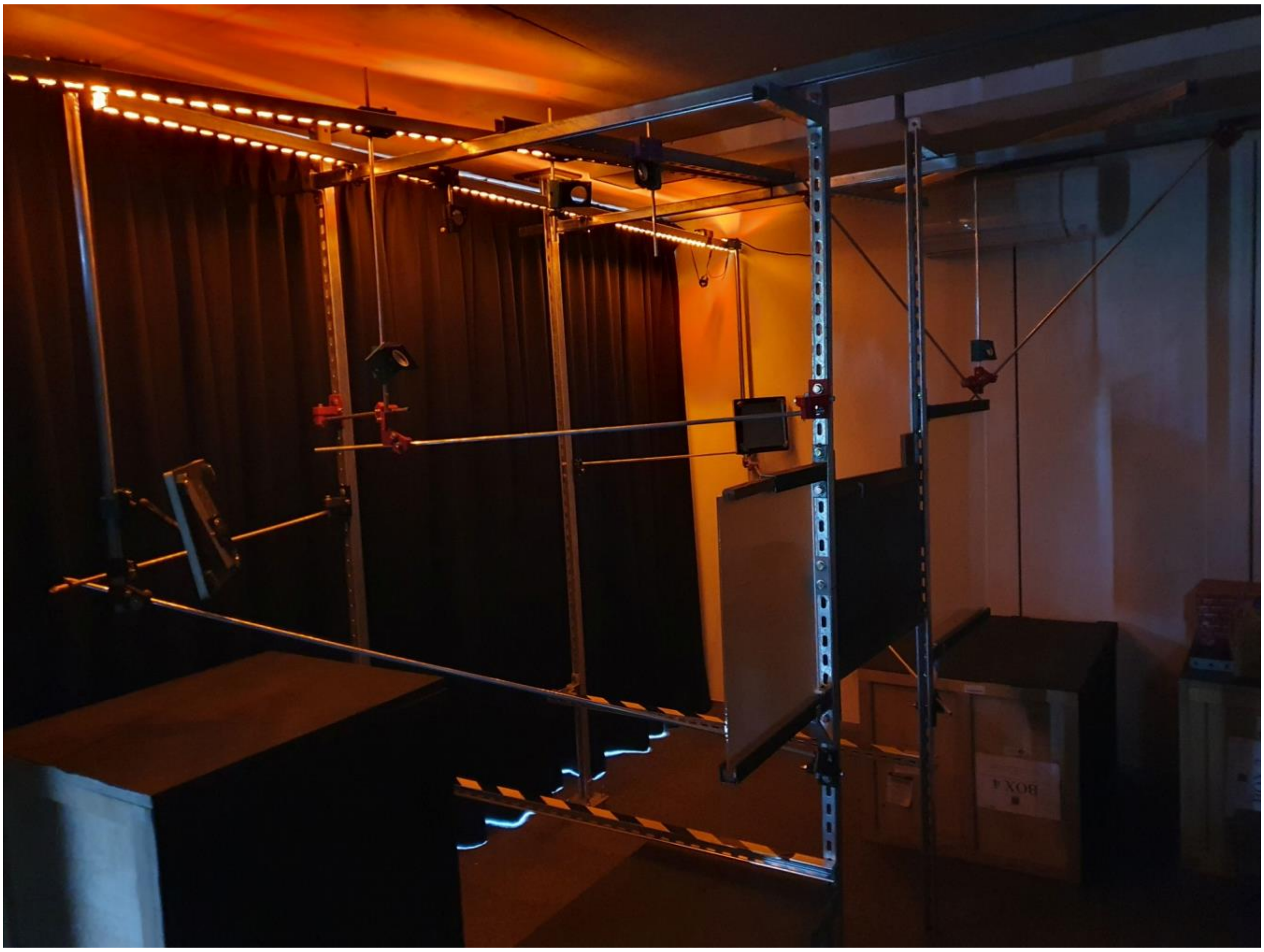
5. VISION

The aim of the pulse laser holography studio is to enable artists and researchers to create holograms. These projects are instrumental in pushing the medium forward and fostering dialogue around holographic concepts. We have built this studio to be part of an international network of facilities available for creativity and innovation. As the offer of online courses and resources grows our aim is contribute to online resources and to be a node for practical collaboration and experimentation.

At the time of writing this is the only studio in Australia, and one of few in the world, where artists and researchers can gain a tactile understanding of holography.

In addition to the pulse laser camera, the studio has a small table-top set-up with a diode laser for experimentation and workshops. If funding allows we would add a digital printer. We are looking to collaborate with other facilities to support artists to make digital holograms.

The pulse laser holography studio with enhance the technology driven artist residencies offered by the Lake Arts Precinct, with artist also able to access the Multi-Arts Pavilion *mima* that is equipped with a 360-degree 4m high projection environment and the Fab Lab maker space. The studio is also a centre for collaborative research and learning with the University of Newcastle.



Our vision is that this pulse laser holography studio will enhance the regions drive to support innovation and will strengthen international collaboration.

Speleoholography

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ABSTRACT

Several apparatuses were built for making holograms in the cave environment. The main objectives being small size for ease of transport and simple set up. A PL530 laser was chosen to help reduce the size. Conventional optics and fiber optics were used in different constructions yielding acceptable quality holograms.

Keywords: Cave, fiber, hologram, PL530, speleoholography

1. INTRODUCTION

This paper chronicles the author's continuing efforts in speoholography - the making of cave formation holograms, a word derived from the combination the prefix speleo for cave and holography. He built several apparatuses using both conventional optics and multimode fiber optics. Larger diameter multimode fibers have been tested in a simulated cave environment with excellent results.

2. EARLIER WORK

Earlier work was based on a C315M DPSS laser which required a heavy set of batteries. The apparatus using conventional optics was somewhat large and cumbersome[1], Attempts were made to reduce the size of the unit using a simple 1 mm multimode fiber to direct the reference beam and eliminate the need for a spatial filter[2,3]. Some devices were made with the hologram platen remote from the laser by lengths of fiber up to 15 meters.

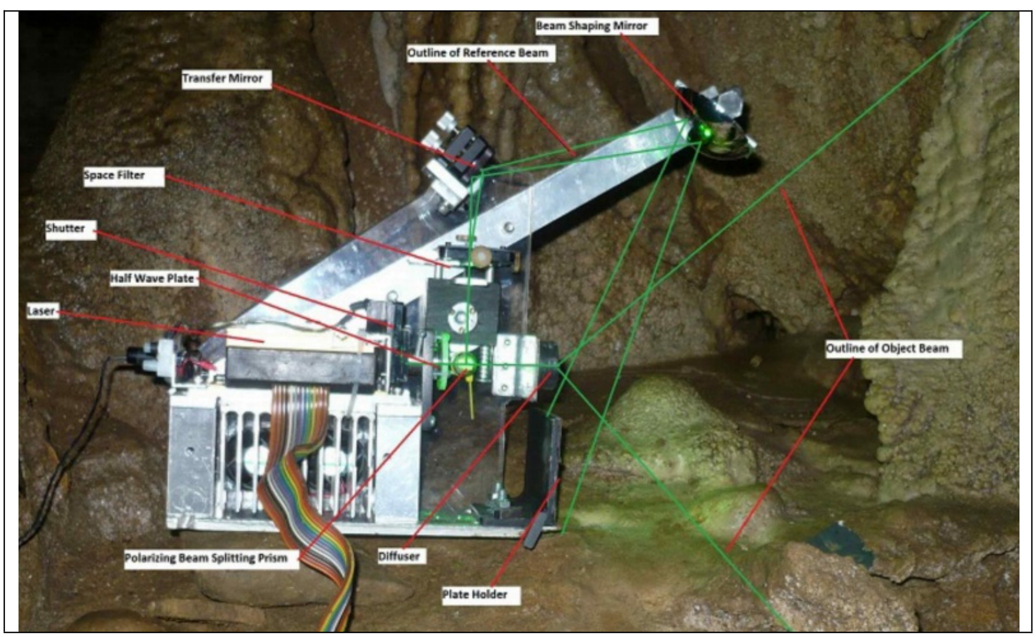

Figure 1. This conventional optics contraption incorporates all the components of an ordinary holography lab including a spatial filter.

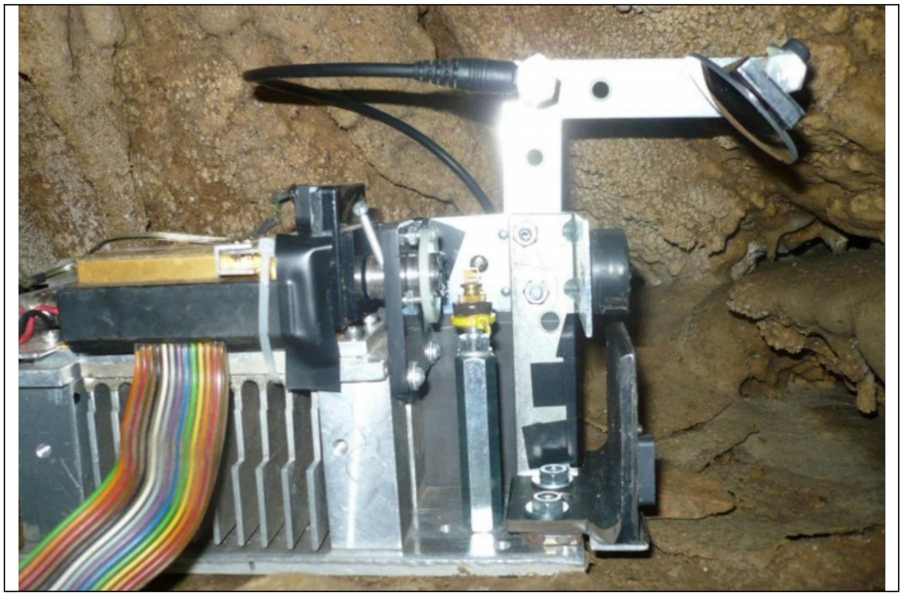

Figure 2. This is an example of a C315M device using a 1 mm fiber and a convex mirror in place of a spatial filter.

Figure 3. A setup with the holography head separated from the laser with fibers carrying the reference and object light.

Figure 4. A typical cave transmission hologram made with a C315M laser reconstructed with a 594 nm HeNe laser.

3. RECENT WORK

A PL530 laser was substituted for the C315M to reduce the size and weight. In one setup a spatial filter was used to ensure a clean reference beam. A convex mirror was put in the reference beam to make it diverge enough to adequately cover the plate. Another setup used a 1 mm fiber instead of a spatial filter. The PL530 has an internal heater for the frequency doubler that requires very fine adjustment. The rest of the unit needs a TEC and well-designed feedback mechanism for stable operation. Several circuits have been tried.

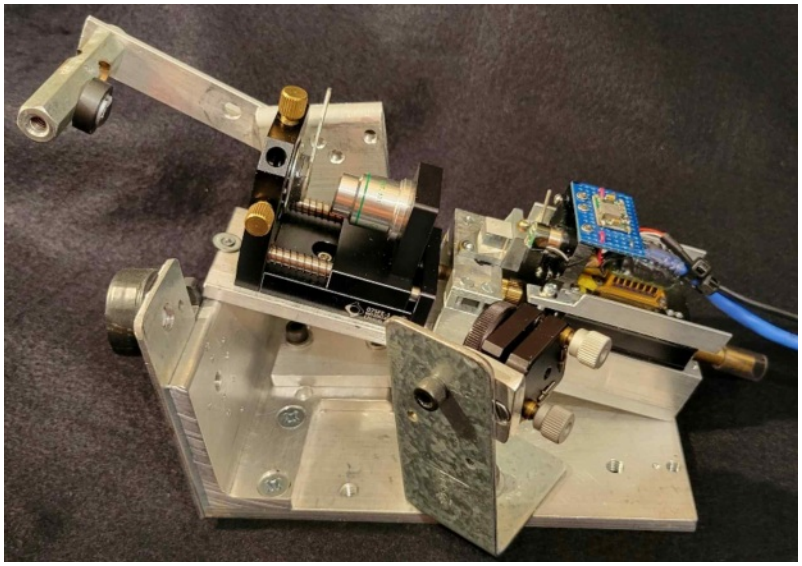

Figure 5. This device, like the apparatus of Figure 1, has all the basic components of an ordinary holography lab but in a smaller package made possible by the much smaller PL530 laser. The unusual, sloped platform holding the laser, variable beamsplitter and spatial filter is to minimize the number of mirrors needed to direct the reference beam. A rod extends under the laser to adjust the Z axis of the space filter.

Figure 6. This PL530 device uses a 1 mm fiber to direct the reference beam and eliminate the spatial filter. The variable beamsplitter was replaced with a fixed ratio beamsplitter to further simplify it.

4. PRESENT WORK

It has been posted on the facebook holography forum that the output of larger core fibers rival that of a spatial filter, 3mm diameter being optimum[4]. My present efforts therefore are based on 3mm fibers.

Figure 7. The output of a 3mm fiber has a few artifacts but is clean enough to be used for a reference beam.

Figure 8. Short 3mm fibers maintain some polarization as indicated by the two faint dark triangular projections after passing through the axis finder in the foreground. The polarization axis can be rotated by twisting the fiber.

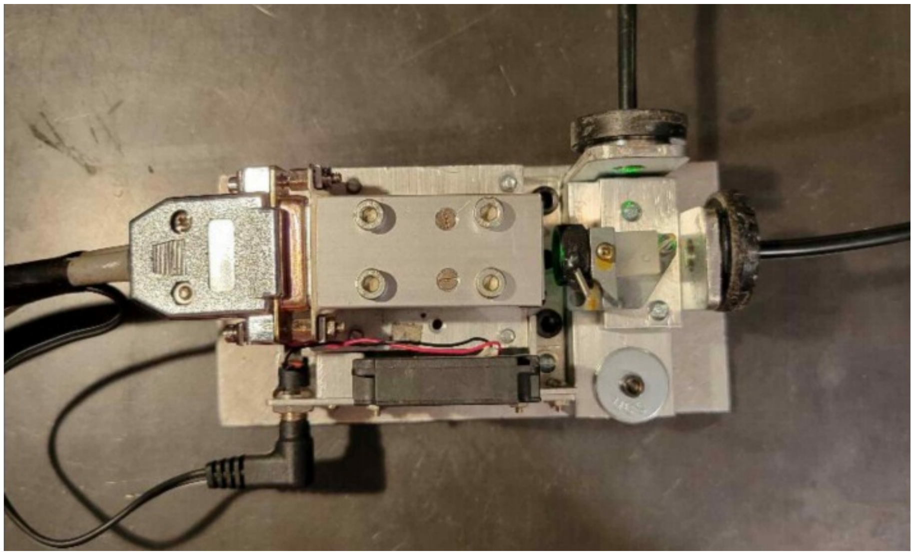

Figure 9. The fibers have larger diameters than the laser beam, they are therefore easily coupled. Each fiber is attached to a magnet that can slide around until the maximum output is found at the other end of the fiber. Pictured here is a PL530 laser aiming through a half wave plate to a polarizing beamsplitter and then to the object and reference fibers.

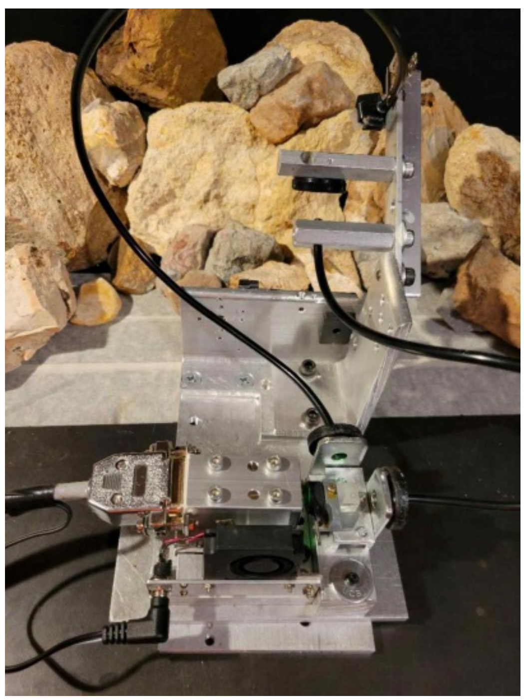

Figure 10. This is an experimental setup using a PL530 laser and 3mm fibers with a pile of rocks in the lab to simulate a cave environment. The reference beam bounces off a flat mirror and down to the plate. The object light is spread by a diffuser located at the top of the apparatus.

Figure 11. This is the resulting hologram from the setup shown in figure 10. It is reconstructed with a green laser diode.

5. FUTURE WORK

Given the satisfactory results of using the larger core fibers for both the reference and object beams, all my future works will probably use them.

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A study on cloud remote rendering method for visualizing volume data of holographic AR glasses

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Abstract

Holographic AR (Augmented Reality) glasses are designed to overlay digital information onto the real world, providing an immersive experience that enhances the user's perception of reality. To efficiently use these glasses, research is required on data processing from the perspective of low-latency methods for 3D volume data. In this study, we propose a cloud-based remote rendering method for 3D volume data with low latency service. To achieve this, we compared it with the existing loading-based rendering method. Our results show that a stable and low-latency service is possible with our proposed method.

Keywords: Cloud, Holographic AR Glasses, Remote Rendering, Smart Glasses, Volume Data

1. Introduction

Holographic AR glasses serve as a type of AR display, overlaying digital information onto the real world and providing users with an immersive experience that enriches their perception of reality [1]. As AR technology has matured, its applications have expanded to include areas such as pedestrian navigation and cultural heritage [2]. However, despite their increasing popularity, AR glasses still face performance limitations compared to traditional computers, prompting research into low-latency methods for content delivery.

In this paper, we propose a cloud-based remote rendering method for 3D volume data that ensures low-latency services. We validate our method by comparing it with the existing loading-based rendering approach using the Meta Quest Pro. The findings indicate that our proposed method allows for stable and low-latency services. This research aims to highlight technical advancements in enhancing the user environment of holographic AR glasses and explore the practical applicability of these advancements.

2. Related Works

Several studies have explored the potential of cloud-based rendering for augmented reality as a means to overcome the performance limitations of AR devices, such as holographic AR glasses. Mobile Edge Computing (MEC): MEC is an approach proposed to address the performance constraints of AR devices. By placing computing resources closer to users at the network edge, MEC reduces latency and bandwidth consumption for AR applications [3]. MEC has been researched in conjunction with cloud rendering, offloading rendering tasks to edge servers to provide an efficient solution for AR glasses.

Adaptive Streaming: Adaptive streaming technology optimizes the performance of cloud rendering for AR applications. It dynamically adjusts the quality of rendered content based on the user's network conditions and device capabilities, ensuring a seamless and uninterrupted user experience [4]. WebRTC (Web Real-Time Communication)-Based Streaming: WebRTC is a technology that facilitates real-time communication between browsers and devices without requiring any additional plugins or extensions [5]. It has been utilized for cloud remote rendering, delivering 3D volumetric data using a streaming approach. Cloud rendering systems use WebRTC to establish Peer-to-Peer (P2P) communication within internal networks, ensuring low-latency, real-time data transmission.

Figure 1 below illustrates the structure diagram of WebRTC. Clients connect with each other via a Signaling Server. A TURN (Traversal Using Relays around NAT) Server is used as a relay for messages when direct connections between clients are not permitted. Data sent from Unity is encoded and transmitted to the WebRTC server. The client, utilizing an application, connects and receives the encoded data after interfacing with Unity through the signaling server. The architecture outlined here targets a single server-to-peer relationship, but it is possible to design architectures that allow multiple clients to connect for a shared streaming experience.

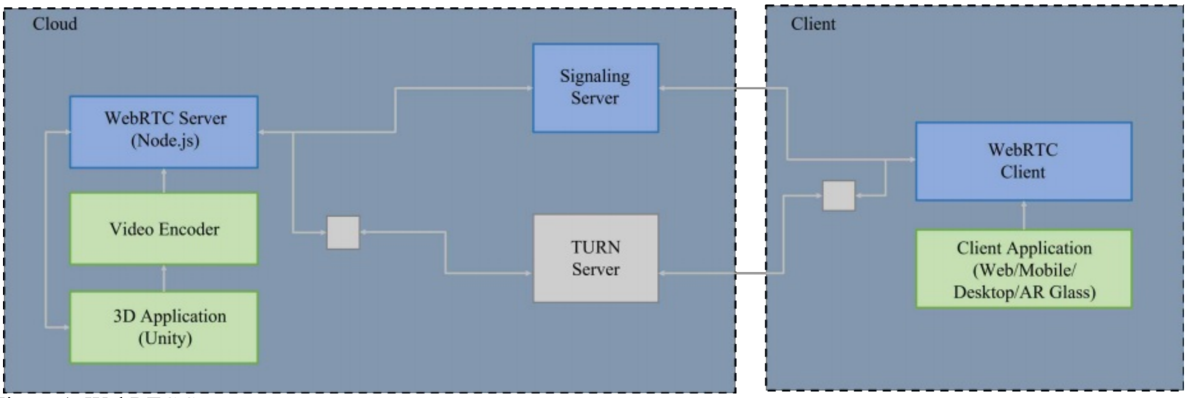

Figure 1. WebRTC Structure

3. Proposed Method

This study compares the latency of traditional loading-based rendering and cloud remote rendering for generating 3D volume data. We measured the time required for 3D volume data to render after accessing a webpage containing the data using the Meta Quest Pro. Figure 2 illustrates the structure and latency of cloud remote rendering when generating 3D volume data with Meta Quest Pro. In this procedure, a user connects to the system, and the client locally generates visual feedback. The user's movements are conveyed to the server, which in turn updates these movements. This updated data is then relayed back to the client and continually refreshed on the AR Glass display. We define "Motion Latency" as the time interval from the user accessing the system to the data display on the Streaming AR Glass Screen. We also introduce the term "Unity Virtual Camera Updates Latency", denoting the time duration for movement updates post user access.

Figure 3 presents a comparison of rendering latency measurements between the two methods. Method (a) applies loading-based rendering and downloads the 3D volume data upon access. Once the download is complete, the model is rendered on the Meta Quest Pro. Conversely, Method (b) uses cloud remote rendering, transmitting data to Unity, which in turn provides 3D volume data through the server upon access. Once a connection is established, the data sent by Unity is rendered on the Meta Quest Pro. We conducted this measurement to ascertain the rendering time of the 3D volume data on Meta Quest Pro using both methods.

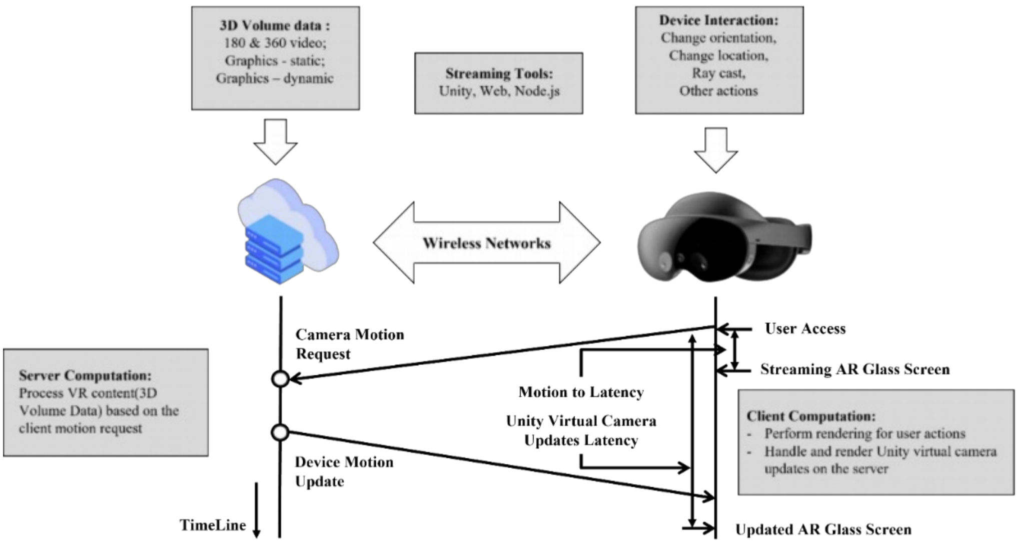

Figure 2. Meta Quest Pro Cloud Remote Rendering System

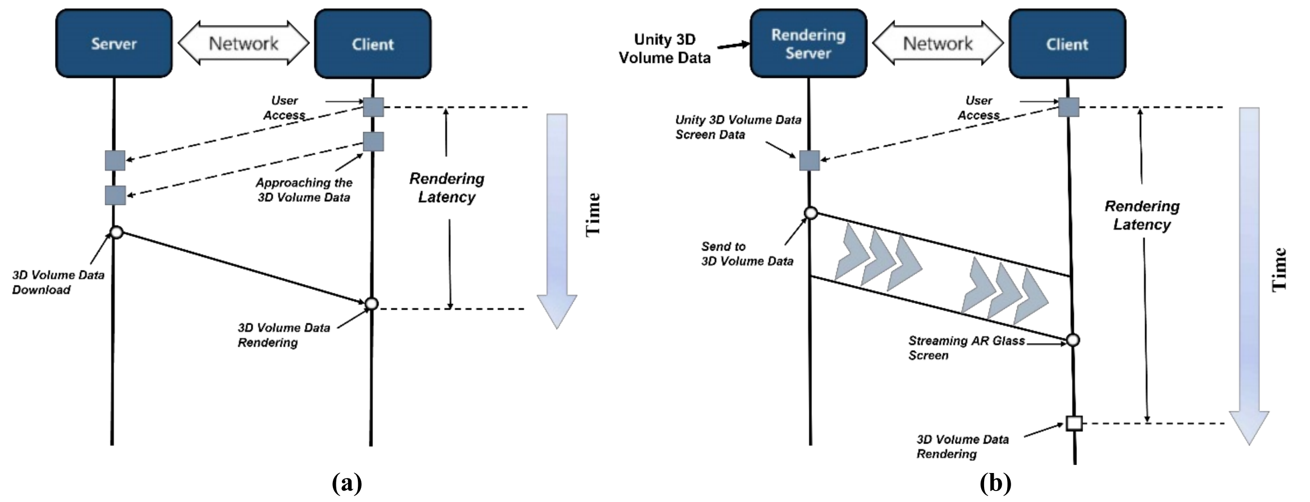

Figure 3. 3D Volume Data Rendering Latency

(a) Loading-Based Rendering, (b) Cloud Remote Rendering

4. Experimental Results

The experiment was carried out with the same device, involving 3D volume data sizes of 100MB and 500MB, within a 300Mbps internet environment. The timer was initiated at the point of user web page access, and we measured the time required to render the 3D volume data on the screen. Moreover, we evaluated the performance of cloud remote rendering by assessing the Frames Per Second (FPS). Table 1 delineates the specifications of the equipment used in the experiment.

Table 1. Experimental Environment.

	Meta Quest Pro	**Computer**
CPU	Qualcomm Snapdragon XR2+	Intel Core i7-10700K – 3.8GHz
GPU	Adreno 650	NVIDIA GeForce RTX 3070
RAM	12GB	32GB
OS	Qualcomm Snapdragon 662	Windows 10

Equation (1) calculates the variance. Where, n is the number of measurements, x is the measured result value, and m is the average value. Equation (2) is the square root of the variance to obtain the standard deviation. The standard deviation was calculated to find a stable method.

$$\text{Variance} = \frac{(x_1-m)^2 + (x_2-m)^2 + (x_3-m)^2 + \ldots + (x_n-m)^2}{n} \quad (1)$$

$$\text{Standard Deviation} = \sqrt{\frac{(x_1-m)^2 + (x_2-m)^2 + (x_3-m)^2 + \ldots + (x_n-m)^2}{n}} \quad (2)$$

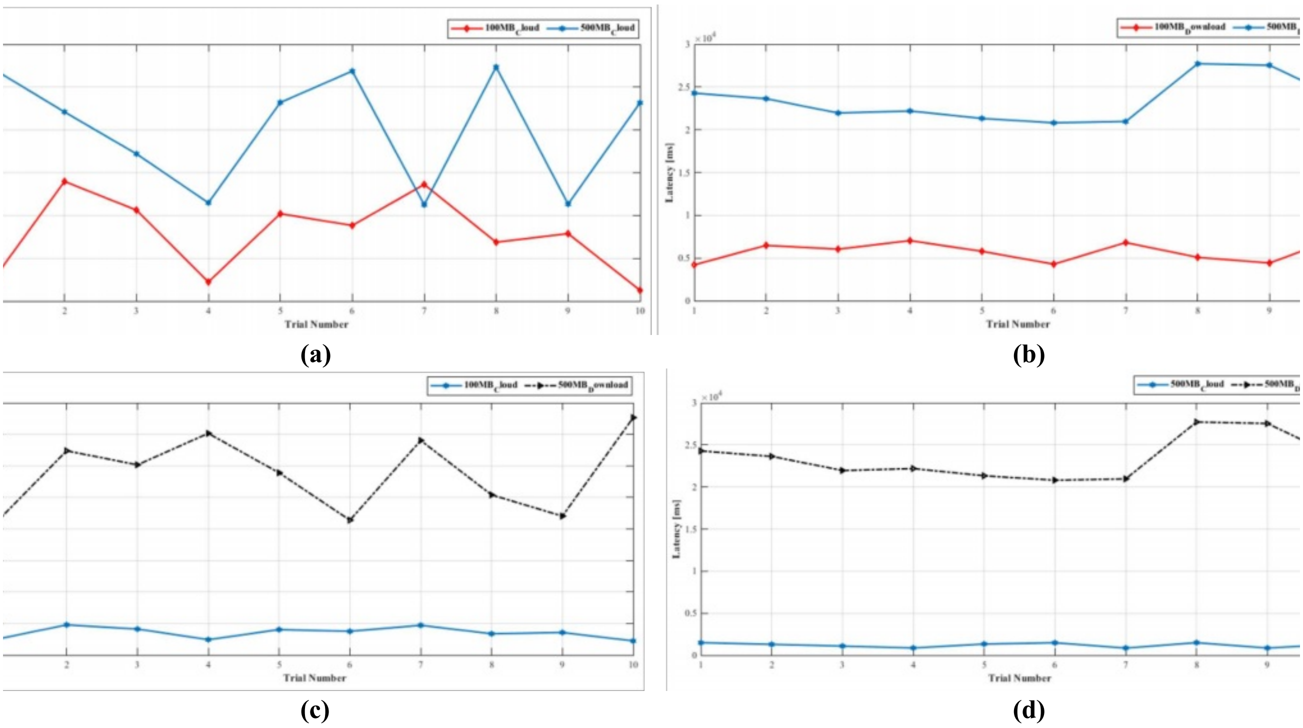

Figure 4. 3D Volume Data Rendering Latency

(a) 100 MB 3D Volume Data Cloud rendering, (b) 500 MB 3D Volume Data loading,

(c) 100MB 3D Volume Data Comparison of Latency, (d) 500MB 3D Volume Data Comparison of Latency

Figure 4 and Table 2 each display the latency results, measured ten times, for both cloud remote rendering and loading-based rendering on the Meta Quest Pro. For cloud remote rendering, the minimum, maximum, and average latency times for rendering 3D volume data are 453ms, 972ms, and 714ms, respectively, for 100MB data, with a standard deviation of 176ms. For 500MB data, these figures are 854ms, 1497ms, and 1209ms, respectively, with a standard deviation of 256ms. For loading-based rendering, the minimum, maximum, and average latency times are 4198ms, 7540ms, and 5570ms, respectively, for 100MB data, with a standard deviation of 1158ms. For 500MB data, the latency times are 20833ms, 27824ms, and 23453ms, respectively, with a standard deviation of 2404ms.

Figure 5 is a graph measuring the FPS of cloud remote rendering over one minute, and Table 3 provides the average FPS. The FPS for cloud remote rendering registers at 125 FPS for 100MB data and 40 FPS for 500MB data. The results suggest that cloud remote rendering performs in real time, with low latency and stable FPS, indicating that the proposed method can provide a stable, low-latency service.

Table 2. Cloud Remote Rendering Latency

Method	Model Capacity (MB)	Maximum Latency (ms)	Minimum Latency (ms)	Average Latency (ms)	Standard Deviation (ms)
Cloud Remote Rendering	100	972	453	713.5	176.44
	500	1497	854	1209.0	256.30
Loading-Based Rendering	100	7540	4198	5570.2	1158.21
	500	27824	20833	23452.7	2403.64

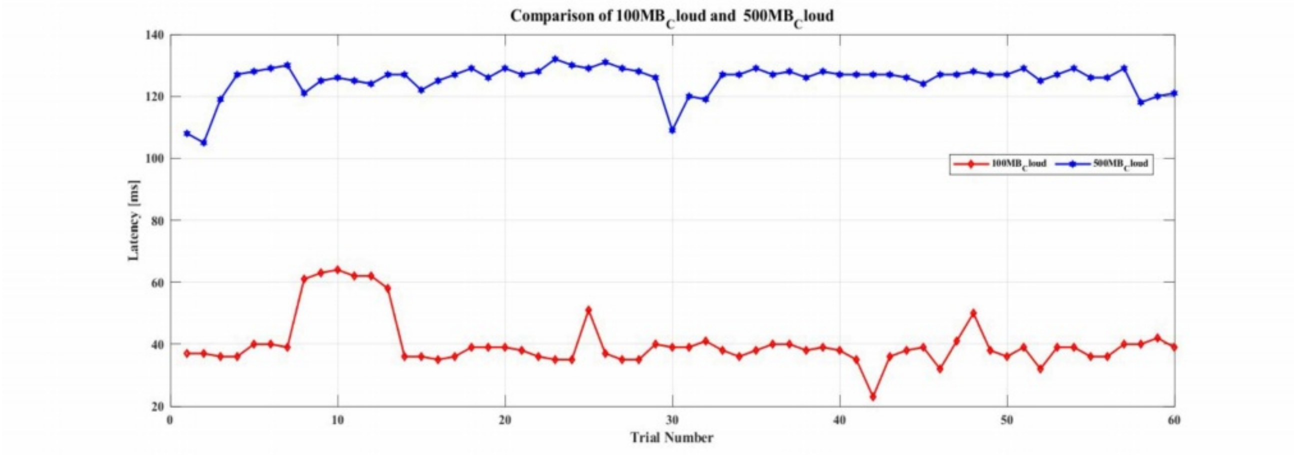

Figure 5. Cloud Remote Rendering Performance

Table 3. Performance Comparison of each Model Capacity in Cloud Remote Rendering

Model Capacity (MB)	FPS
100	125.38
500	40.22

5. Conclusion

In this paper, we investigated cloud remote rendering for Holographic AR glasses, which overlay digital information onto the real world, thereby enhancing users' immersive experiences. Despite the growing prevalence and usage of AR glasses, performance limitations compared to traditional computers necessitate further research into low-latency rendering methods for 3D volume data. We proposed a cloud-based remote rendering method to provide low-latency 3D volume data rendering. This method was compared with the existing loading-based rendering method using Meta Quest Pro, demonstrating that the proposed method can deliver stable and low-latency services.

This research contributes to technological advancements that improve the user environment of Holographic AR glasses and explores the practical applicability of the proposed method. The experiment was conducted in a network environment with a speed of 300Mbps, using 3D volume data sizes of 100MB and 500MB. The results demonstrate that the proposed cloud-based rendering technology effectively addresses performance limitations, enabling low-latency remote rendering in Holographic AR glasses. Future research is required to investigate the applications of Holographic AR glasses in various fields. Please note, while this revision improves grammar and clarity, it is crucial to confirm the technical accuracy of the content based on your specific research. The content structuring and organization seem to follow common conventions for scientific papers, and each section serves its intended purpose.

Acknowledgement

This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the ITRC(Information Technology Research Center) support program(IITP-2023-2020-0-01846) supervised by the IITP(Institute for Information & Communications Technology Planning & Evaluation). This work was supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT (No. 2020-0-00922, Development of holographic stereogram printing technology based on multi-view imaging). This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ICAN (ICT Challenge and Advanced Network of HRD) program (IITP-2022-RS-2022-00156215) supervised by the IITP (Institute of Information

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Comparative study of IoT sensor protocol of holographic AR glasses

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Abstract

Holographic AR glasses provide processing and visualization of IoT sensor data, and as such, research is required to optimize transmission time for different sensor data processing methods. In this study, we conduct a comparative analysis of three popular IoT protocols - MQTT, CoAP, and HTTP - to transmission time consumption when processing sensor data. Our experiment measures transmission time while processing sensor data according to each protocol. The results of this study will provide insights into the transmission time of different IoT protocols for use in Holographic AR glasses, helping to optimize their performance and enable efficient large-scale sensor data processing.

Keywords: Holographic AR Glasses, IoT Protocol, IoT Sensor, Large-scale Data, Smart Glasses

1. Introduction

Holographic AR (Augmented Reality) glasses and low-latency IoT sensor data processing require efficient communication protocols to ensure seamless and real-time data transmission. In this study, we conducted an evaluation of the transmission time for three prominent IoT communication protocols: MQTT, CoAP, and HTTP. The objective was to assess their performance and suitability for applications involving holographic AR glasses and low-latency IoT sensor data processing. The results showed that MQTT exhibited periodic latency but generally had low transmission times. CoAP demonstrated the lowest transmission times, while HTTP showed relatively longer transmission times. This research provides insights into optimizing data transmission time in holographic AR glasses and IoT environments, contributing to performance improvements and efficient data processing.

2. Related Works

Currently, there is active research underway to address the latency issues associated with IoT sensor data. The rapid advancement of IoT technology and its applications has emphasized the significance of real-time data processing and latency reduction. Consequently, research efforts are being directed towards the development of data processing and communication technologies that enable real-time processing and latency reduction through the utilization of edge computing [1].

2.1 Edge computing

Edge computing is one of the methods employed to reduce latency in IoT applications. It optimizes latency by utilizing multiple distributed computing nodes within the network to decentralize data processing from centralized data centers. Research is focused on edge computing architectures, data processing and distribution, as well as local caching and cache management, with the aim of minimizing latency [2].

2.2 Realtime communication

Various technologies and algorithms are utilized in IoT systems for real-time data processing. Techniques such as data streaming, parallel processing, distributed processing, data prediction and compression, and event processing are analyzed to propose methods for real-time data processing and latency reduction [3]. These research efforts focus on investigating different approaches and technologies for real-time processing and latency reduction of IoT sensor data, including holographic AR glasses and other AR devices. IoT systems can employ hundreds of messaging protocols to meet diverse requirements. Selecting an efficient communication protocol is crucial to mitigate server overload and reduce latency. However, no single protocol can perfectly fulfill all requirements simultaneously, including energy efficiency, security, and reliability [4].

Therefore, research is conducted to compare and analyze various protocols, considering performance, in order to select and optimize the most suitable protocol for specific environments or applications. This research aims to facilitate real-time processing and latency reduction of IoT sensor data, enabling more efficient and reliable data communication in applications such as holographic AR glasses.

3. Experimental Environment

In this study, we constructed servers for three representative IoT communication protocols: MQTT, CoAP, and HTTP, and evaluated and compared the transmission time of sensor data. The specific experimental environment is as follows.

3.1 Server construction

The servers were built using Amazon Web Services (AWS) Elastic Compute Cloud (EC2). The Ubuntu 20.04 version was chosen as the operating system for the servers. We constructed an MQTT Broker for the MQTT protocol, a CoAP server for the CoAP protocol, and an HTTP server for the HTTP protocol. Table 1 represents the server environment utilized in the study.

Table 1. Experimental Environment.

AWS (EC2)	
Type	T2 micro
CPU	vCPUs, 2.5 GHz
Ram	1G
OS	Ubuntu 20.04
Web Server	Apache 2.4.41
DB	SQLite 3.31.1
MQTT	Mosquitto 1.6.9
CoAP	Node.js 16.19.1

3.2 Protocol comparison

Figure 1 illustrates the communication architectures for each protocol. (a) MQTT is divided into a broker server, publisher, and subscriber. The broker server operates by pushing data to MQTT subscribers. Publishers share their specific information by publishing it, while subscribers register for topics of interest to receive data from publishers. (b) The HTTP protocol operates over TCP/IP, enabling stable communication. Data can be transmitted from one device to another without being corrupted. Data is transmitted based on IP addresses and URLs. Since connections are dynamically changed, they are established and released each time access is made and data transmission is completed. CoAP has two methods of message transmission. The first method, shown in (c), involves sending non-confirmable (NON) messages. The message ID is used for message deduplication. The second method, shown in (d), is reliable message transmission. It involves sending confirmable (CON) messages, and the message identifier (Message ID) included in them is also present in acknowledgment (ACK) messages. If the recipient successfully receives the data or request, an acknowledgment message is sent. In this paper, non-confirmable messages were used.

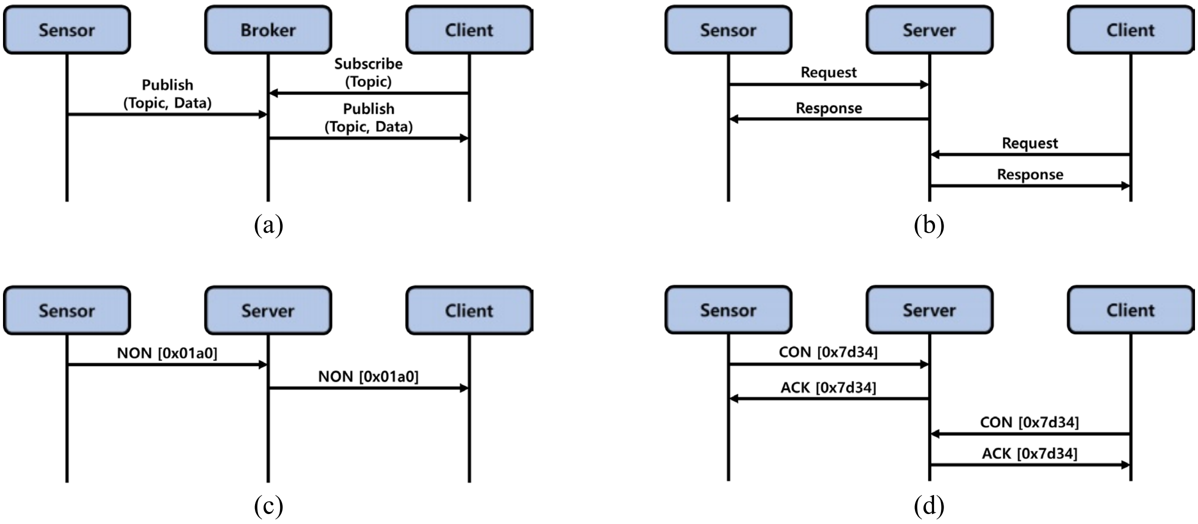

Figure 1. Communication Architecture

(a) MQTT, (b) HTTP, (c) CoAP- non-Confirmable, (d) CoAP-Confirmable

3.3 Data amount and transmission time analysis

We analyzed the data amount and transmission time using the Wireshark program. Wireshark is a program used to capture and analyze network packets, enabling real-time monitoring and recording of the data transmission process. In this study, Wireshark was utilized to analyze the packets generated during the data transmission between the Arduino board and the server, allowing us to measure the transmission time of the data. Figure 2 represents the flowchart of the sensor data communication using the ESP-8266 board and the DHT11 sensor. The transmission time was measured as the duration from the start of data transmission until its completion. Figure 3 is the system structure diagram.

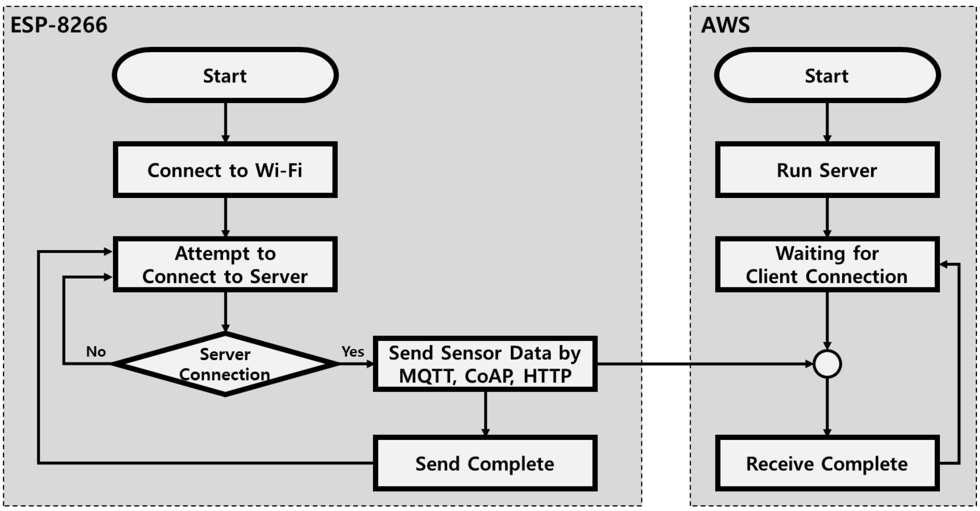

Figure 2. Data Communication Flow Chart

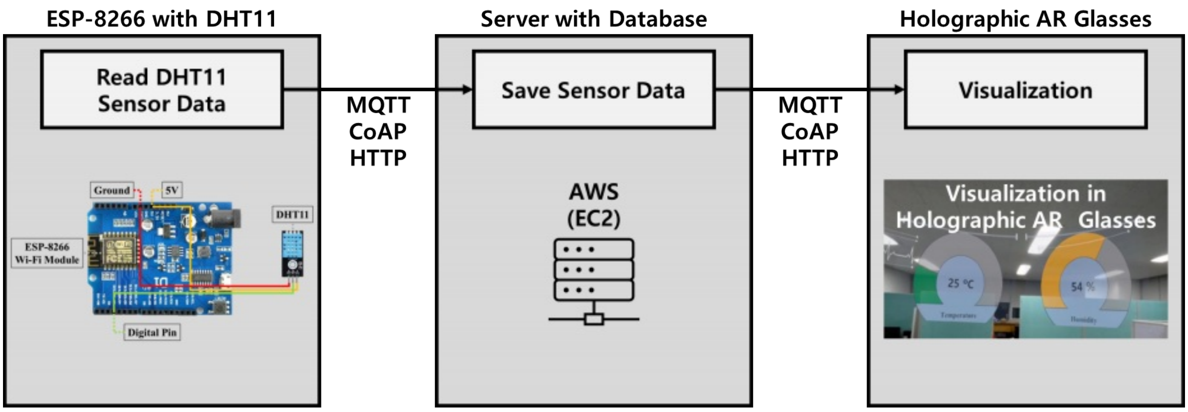

Figure 3. System Structure Diagram

4. Experimental Results

In the experiment, we conducted 10 rounds of data transmission using MQTT, CoAP, and HTTP protocols. We monitored and analyzed real-time communication using Wireshark. The results of the analysis are presented. Figure 4 presents the comparison of data transmission times for the three protocols. For the MQTT protocol, it was observed that except for the 2nd and 7th rounds, a transmission time of approximately 1ms occurred. This is due to MQTT protocol sending pings to confirm the connection with the broker server. The average transmission time for MQTT was measured to be 19.7ms, with a standard deviation of approximately 42.29. The CoAP protocol consistently showed the lowest transmission time of 1ms in all 10 measurements. This result can be attributed to the lightweight nature and efficient communication mechanism of the CoAP protocol. The HTTP protocol exhibited an average transmission time of approximately 169ms. It had a longer transmission time compared to MQTT. However, the standard deviation for HTTP was approximately 12.77, indicating relatively stable results when compared to MQTT.

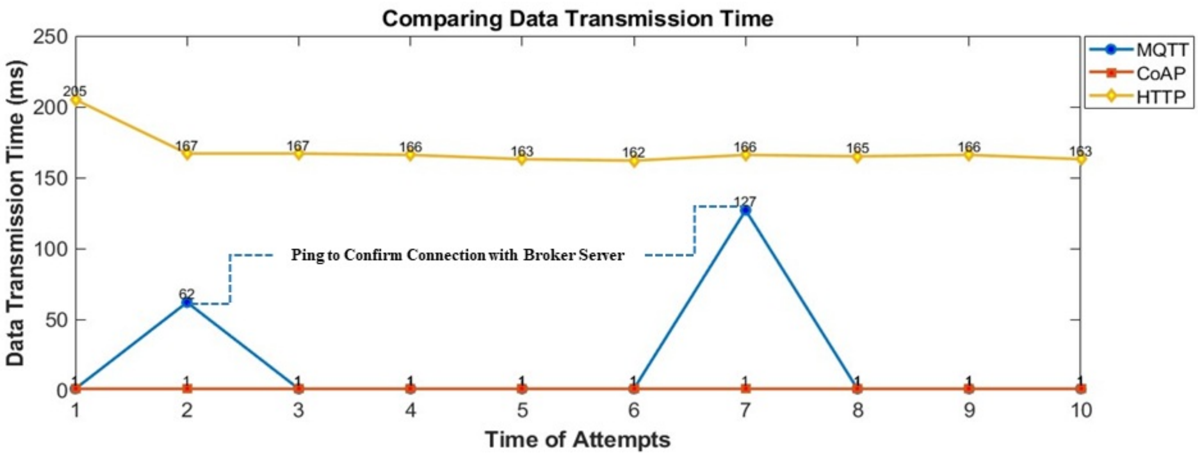

Figure 4. Comparing Data Transmission Time

Figure 5 depicts the comparison amount of data transmitted per round for the three protocols. For MQTT, the average amount of data per round was 124.6 bytes, with a standard deviation of 42.29. It indicates that MQTT has the highest variability among the three protocols in terms amount of data per round. CoAP had an average amount of data of 111.8 bytes, with a standard deviation of 8. It exhibited the lowest average amount of data among the three protocols, indicating its lightweight nature. The HTTP protocol consistently showed amount of data of 448 bytes in all 10 measurements, indicating a consistent amount of data. However, due to the larger amount of data, it resulted in relatively higher latency compared to the other protocols.

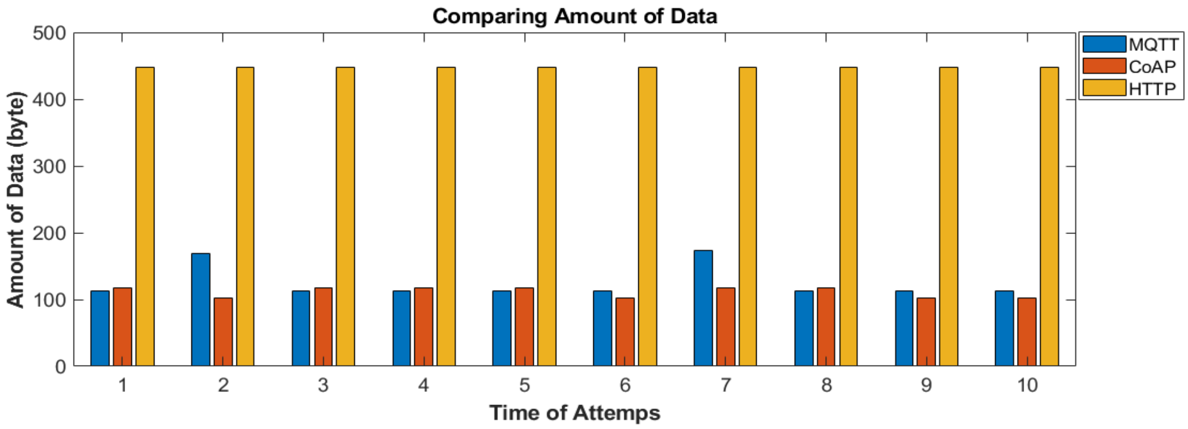

Figure 5. Comparing Amount of Data

5. Conclusion

In this study, we evaluated the transmission time of MQTT, CoAP, and HTTP protocols for holographic AR glasses and low-latency IoT sensor data processing. The experimental results revealed that MQTT exhibited periodic latency due to the nature of maintaining the connection. CoAP demonstrated the lowest transmission time, while HTTP showed relatively longer transmission times. Based on these findings, it is crucial to carefully select and optimize communication protocols for holographic AR glasses and other application domains. Consideration of the latency of the chosen protocol is essential for performing appropriate settings. This research provides insights into optimizing data transmission time in the context of holographic AR glasses and IoT environments, contributing to performance improvements and efficient data processing.

Acknowledgement

This research is supported by Ministry of Culture, Sports and Tourism and Korea Creative Content Agency (Project Number: R2021040083). This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the ITRC(Information Technology Research Center) support program(IITP-2023-2020-0-01846) supervised by the IITP(Institute for Information & Communications Technology Planning & Evaluation). This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ICAN(ICT Challenge and Advanced Network of HRD) program (IITP-2022-RS-2022-00156215) supervised by the IITP(Institute of Information & Communications Technology Planning & Evaluation).

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Development of holographic technology for AR near-eye display with focus cue

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ABSTRACT

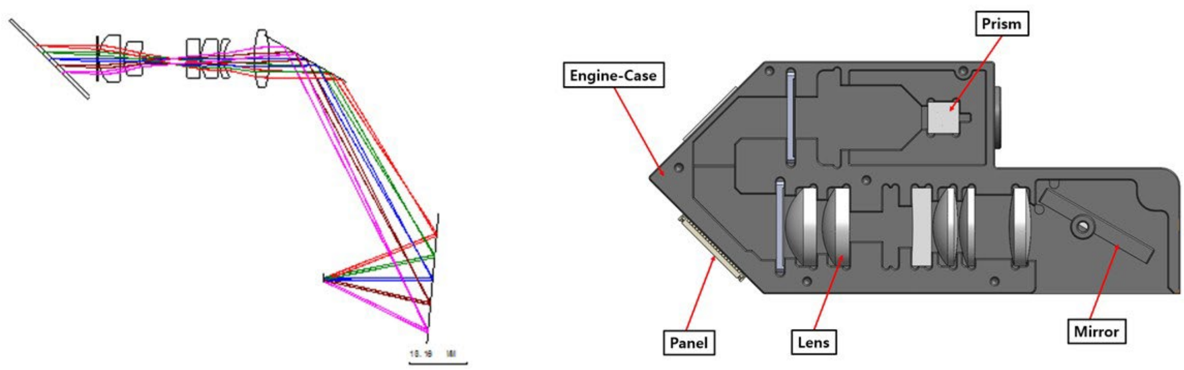
Due to the growing popularity of augmented reality (AR) head-mounted displays (HMDs), researchers are actively investigating accommodation display technologies that can enable dynamic eye focusing in AR HMDs, surpassing the limitations of fixed focal planes. Hologram technology has garnered extensive research attention for its potential in enhancing immersion by providing full three-dimensional information to the users. Nevertheless, there is a pressing need to improve quality of the holographic images and reduce the weight of the display module. In pursuit of a lightweight AR holographic projection module, we employed an image combiner integrated with a lens holographic optical element (HOE). This paper introduces a lightweight holographic AR projection optical system that employs an HOE developed by the Korea Electronics Technology Institute.

Keywords: holographic optical element, augmented reality, near-eye display, hologram

1. INTRODUCTION

The rise of the augmented reality (AR) technology has sparked an increased interest in AR head-mounted displays (HMDs). Researchers are actively exploring accommodation display technologies that can enable eye focusing instead of fixed focal planes in AR HMDs [1]. This is crucial to combat motion sickness and create more immersive experiences of the users. Hologram technology, which utilizes wavefront information of the light to display images in three-dimensional space and induce natural focusing, is being extensively studied for its potential in enhancing immersion [2]. However, there is a need to improve the image characteristics and reduce the weight of the display module. In order to create a lightweight holographic AR projection module, we utilized an image combiner equipped with a lens holographic optical element (HOE). The HOEs have gained significant attention as a promising technology for AR optics due to its thinness and high transparency [3]. In this paper, the lightweight holographic AR projection optical system using an HOE developed by the Korea Electronics Technology Institute is introduced.

2. DESIGNING AND MANUFACTURING OF THE PROJECTION MODULE



(a) (b)

Figure 1. **(a)** An optical simulation of the projection optic system to inject into a lens HOE and **(b)** its detailed design.

In order to address the distortion present in holographic AR images resulting from the lens HOE and off-axis incidence, we conducted optimization of the projection optical system. To mitigate the adverse effects of distortion, it was necessary to fine-tune the parameters of the projection optical system. By employing Zemax OpticStudio, we conducted comprehensive simulations to analyze the behavior of light and optimize the system's performance. The simulations enabled us to evaluate and refine the system's configuration, including the HOE and other optical elements, to minimize distortion and maximize image quality.

Figure 1 shows an optical simulation of the projection optic system and its detailed design. The system consists of four spherical lenses, one aspherical lens, one cylindrical lens, and one mirror. By carefully selecting and positioning these optical elements, we achieved effective correction of optical aberrations in the holographic AR projection system. The combination of the aspherical lens and cylindrical lens played a crucial role in compensating for aberrations, ensuring that the projected holographic images exhibit enhanced clarity and accuracy.

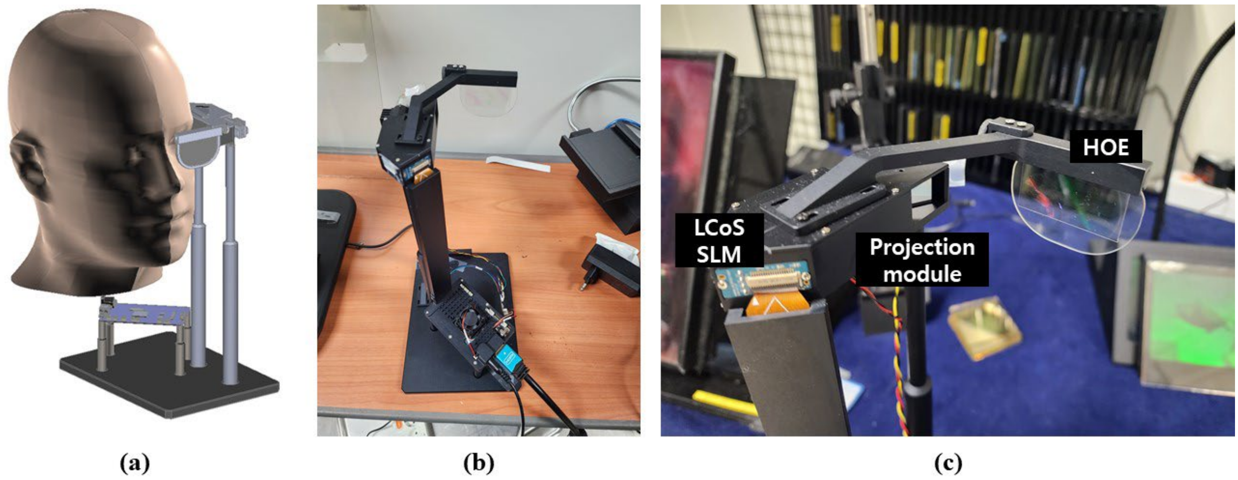


Figure 2. **(a)** A schematic diagram of the designed AR holographic projection module, **(b)** the implemented prototype and **(c)** an enlarged photo of the optical system including the lens HOE.

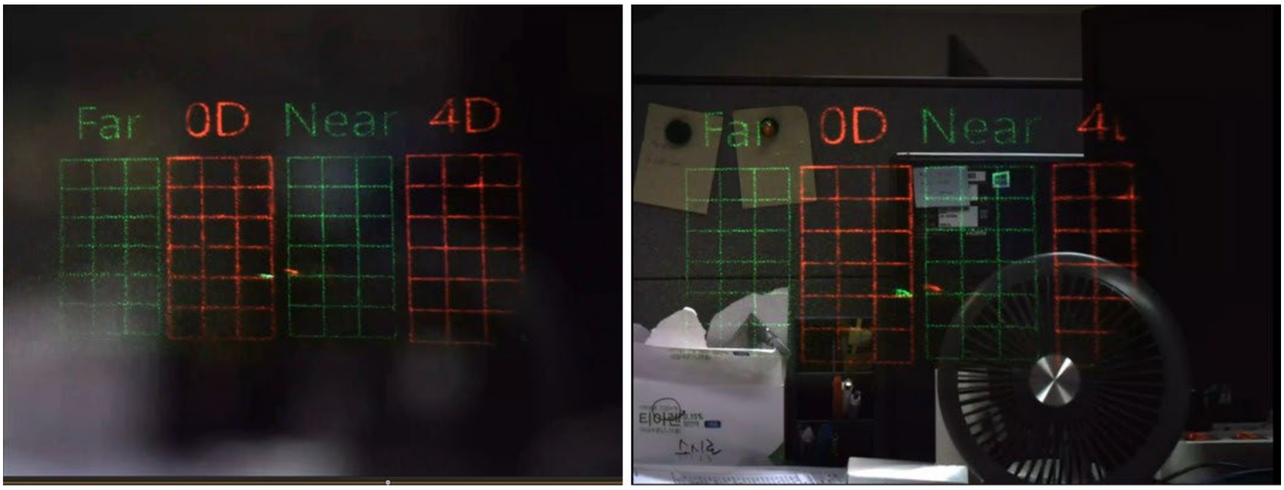
Based on the optical simulation, we implemented a prototype of the holographic AR HMD system. The lens HOE was recorded in both 633 nm and 532 nm wavelength, allowing us to display images in red and green colors. To match the recorded wavelengths of the HOE, 638 nm (red) and 532 nm (green) laser diodes are implemented in the projection module. An LCoS spatial light modulator (SLM) of 1920 x 1080 resolution with 4.5 um pixel pitch is used to display hologram images. The SLM can present 2-colors by using field-sequential-color method. Figure 2 shows the detailed information of the implemented prototype.

3. EXPERIMENTAL RESULTS

Using the prototype of developed holographic AR near-eye display system, we conducted experiments involving the display and capture of the AR holographic images. As shown in Fig. 3, we focused on both nearby (at a distance of 4 diopters) and faraway (at a distance of 0 diopter) objects, observing the changes in grid patterns generated by holograms. It can be noticed that the grid pattern exhibited variations corresponding to the focal distance.

Moreover, we observed that the distortion caused by the imaging system and the lens HOE was effectively corrected, as evidenced by the grid pattern appearing undistorted. The experiments demonstrated the successful compensation of distortions arising from imaging system and the HOE, resulting in improved visual fidelity of the grid pattern.

The experiments validated the system's capability to reproduce accurate and distortion-free holographic content at different focal distances, contributing to a more immersive and visually pleasing AR experience.



(a) **(b)**

Figure 3. The captured hologram images of the **(a)** nearby (at a distance of 4 diopters) and **(b)** faraway (at a distance of 0 diopter) grid patterns.

4. CONCLUSION

In this paper, we present a light-weight holographic AR near-eye projection system that provides focus cues and multi-color images. To achieve a light-weight AR optic, a multi-wavelength recorded (633 nm and 532 nm) lens HOE is implemented. To compensate the image distortion, we optimize the lens group with optical simulation tool. We implement a prototype of the holographic AR near-eye display system and provide experimental demonstrations to validate the effectiveness of our proposed method.

ACKNOWLEDGEMENT

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Asymmetrical holographic optical element recording method for reflected image removing on surface

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ABSTRACT

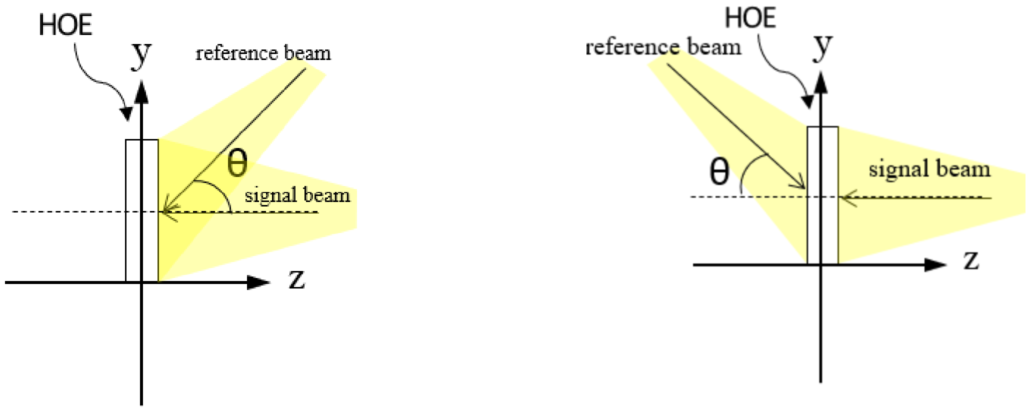
To produce holographic optical element (HOE), a signal beam and a reference beam are interfered on a photopolymer, and the interfered fringe pattern is recorded onto the holographic emulsion. Then holographic images can be displayed by projecting images on the recorded HOE. To increase the clarity of the displayed image, in general, the signal beam and the reference beam are incident on a holographic emulsion with symmetric incident angle. However, we can see both the image reflected by the HOE surface and the diffracted image by the HOE. The HOE reflection of such a projected image acts as a display disturbance factor as a twin image display. To solve this problem, we propose a method and system for manufacturing asymmetric HOE through beam incident angle tilting. When the image is projected onto the HOE produced by the proposed method, it has been confirmed that only one image can be clearly observed without any image overlap.
Keywords: HOE, photopolymer, projecting image, tilting, double image, signal, collimated, reflected

1. INTRODUCTION

Holographic technology can be applied in various fields such as displays, measurement, inspection, printing, and the others. Holographic optical element (HOE) is a diffraction optical component based on holographic technology, which have an advantage of replacing nonconventional optical elements. HOE can be utilized in optical systems to control optical path, incorporate functionalities of lenses, or serve as diverse functional optical components. These HOEs can be fabricated in transmissive or reflective type depending on their intended applications. As shown in Fig. 1(a), in case of transmissive HOE, the signal beam and the reference beam are incident in the same direction with respect to the HOE plane. The incident beams interfere with each other, resulting in an interference pattern that is recorded on the holographic emulsion, which serves as the recording medium [1]. Conversely, in case of the reflective HOE, as depicted in Fig. 1(b), the signal beam and the reference beam are incident in both directions with respect to the HOE plane, forming an interference pattern [2].

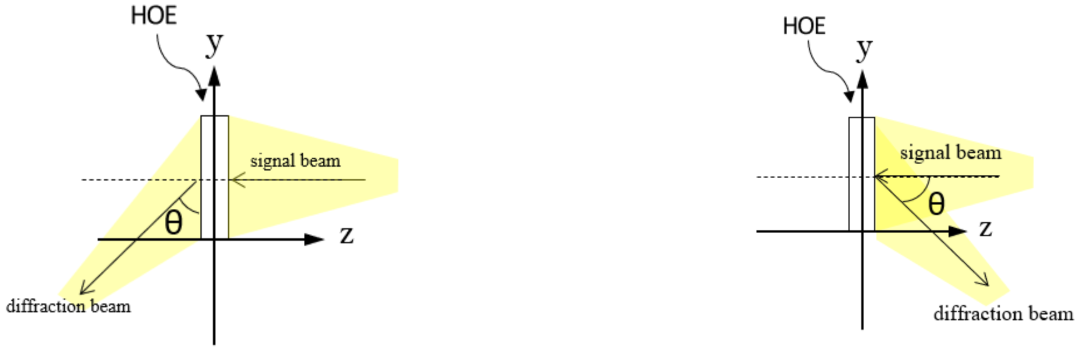
Fig. 2 illustrates how the signal beam is diffracted and emitted by reflective and transmissive HOE. In the case of transmissive HOE, as shown in Fig. 2(a), when the signal beam is incident, the diffracted beam by the HOE passes through with the same optical path as the reference beam used during recording, resulting in emission. The diffractive optical component produced through this process is referred to as a transmissive HOE. On the other hand, reflective HOEs, depicted in Fig. 2(b), act a different behavior. When the signal beam is incident, the diffracted beam by the HOE is reflected with the same optical path as the reference beam used during recording, leading to emission. The diffractive optical component produced through this process is referred to as a reflective HOE.

The reflective HOE depicted in Fig. 1(b) can shows different characteristics depending on the angular difference between the incident signal beam and the reference beam. Generally, based on whether the incident angles of the signal beam and the reference beam are the same or different, they can be classified as symmetric HOE[3, 4] and asymmetric HOE[5]. The optical structures corresponding to these cases are illustrated in Fig. 3. As shown in Fig. 3, when the incident angles of the signal beam and the reference beam with respect to the HOE are $\theta 1 = \theta 2$, it is referred to as a symmetric HOE. On the other hand, when the incident angles are $\theta 1 \neq \theta 2$, it is referred to as an asymmetric HOE.



(a) (b)

Figure 1. Construction of transmissive and reflective HOE recording. (a) Transmissive HOE. The reference beam and the signal beam are incident on the HOE in the same direction with respect to its plane. (b) Reflective HOE. The reference beam and the signal beam are incident on the HOE from opposite directions with respect to its plane.



(a) (b)

Figure 2. Diffraction directions of transmissive and reflective HOE. (a) The incident signal beam is diffracted by the HOE and transmitted in the direction of the reference beam. (b) The incident signal beam is diffracted by the HOE and reflected in the direction of the reference beam.

The reflective HOE depicted in Fig. 1(b) has different characteristics depending on the angular difference between the incident signal beam and the reference beam. Generally, according to the incident angles of the signal beam and the reference beam, they can be classified as symmetric HOE[3, 4] or asymmetric HOE[5]. The optical structures corresponding to these cases are illustrated in Fig. 3. As shown in Fig. 3, when the incident angles of the signal beam and the reference beam with respect to the HOE are $\theta 1 = \theta 2$, it is referred to as a symmetric HOE. On the other hand, when the incident angles are $\theta 1 \neq \theta 2$, it is referred to as an asymmetric HOE.

The advantages of symmetric HOE include a symmetrical structure of the signal beam and reference beam, allowing for suitable optical system configuration and easy control of the optical path and properties of the light. Additionally, due to its symmetrical structure, it may have low power loss and high energy efficiency in laser applications, and in case of display applications, it can enhance the brightness of the displayed images. As compared to symmetric HOE, asymmetric HOE may require more complex system configuration. It may needs precise alignment and adjustment, and thus, errors resulting from alignment can lead to relatively energy loss compared to the recording process of symmetric HOE. However, asymmetric HOE offers advantages in terms of its asymmetric structure, allowing for the implementation of various forms and functionalities, as well as enabling more precise control of light beams [4]. On the other hand, symmetric HOE has the disadvantage of overlapping the projected image and the observer image when used in displays.

Fig. 4 represents a display structure designed to observe the overlapping phenomenon that can occur with symmetric HOE. The image projected from the laser projector is reflected onto the screen, and the image is projected onto the HOE. The projected image can be observed as a virtual image at a certain distance. When symmetric HOE is used in the display structure depicted in Fig. 4, the drawback of overlapping between the projected image and the observer image, as shown in Fig. 5(b), can be observed.

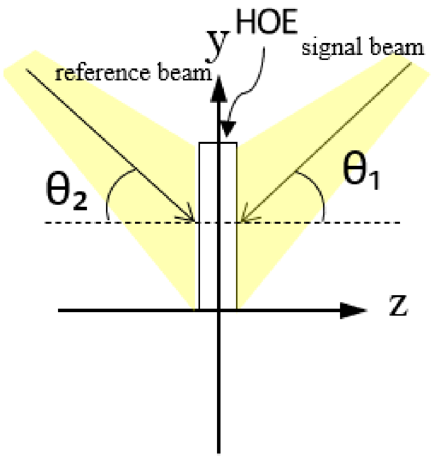


Figure 3. When the incident angles of the reference beam and the signal beam are the same, it is classified as a symmetric HOE. When they are different, it is classified as an asymmetric HOE.

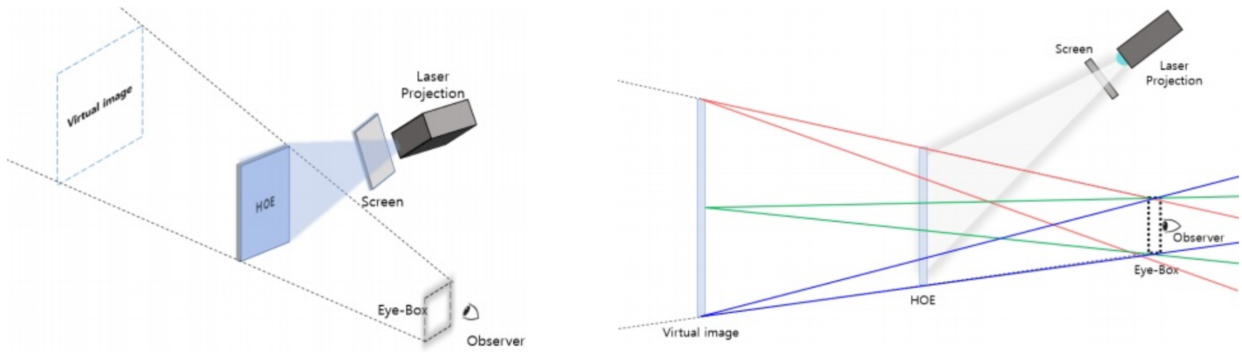
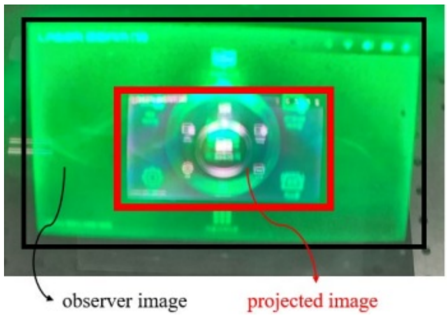


Figure 4. depicts the structure of an HOE display. It consists of a laser projector and a screen, allowing the observer to perceive a virtual image within the eye-box.

In this paper, a symmetric HOE recording method is proposed to eliminate the image overlap phenomenon. To confirm the proposed method, the designed and recorded HOE is applied to a display, and by its display experiment, we confirmed that the previously observed overlapping images caused by symmetric HOE is eliminated, and the corresponding brightness is also increased.

(a)



(b)

Figure 5. Observing images by using a HOE and an image projection system, consisted according to the structure as shown in Fig. 4. (a) with asymmetric HOE, and (b) with symmetric HOE.

2. PROPOSED METHOD

The proposed method, which combines symmetric and asymmetric HOE, is illustrated in Fig. 6. Fig. 6 represents the HOE plane in a 3-dimensional space, where Fig. 6(b) shows the x-z plane and Fig. 6(c) shows the y-z plane. As shown in Fig. 6(b), in the x-z plane, the reference beam and the reference beam are incident at the same angle, following the same method as traditional symmetric HOE. However, as depicted in Fig. 6(c), in the y-z plane, the reference beam and the reference beam are incident at different angles, allowing the production of reflective HOE. Through this fabrication method, the resulting HOE can possess the advantages of both symmetric HOE and asymmetric HOE.

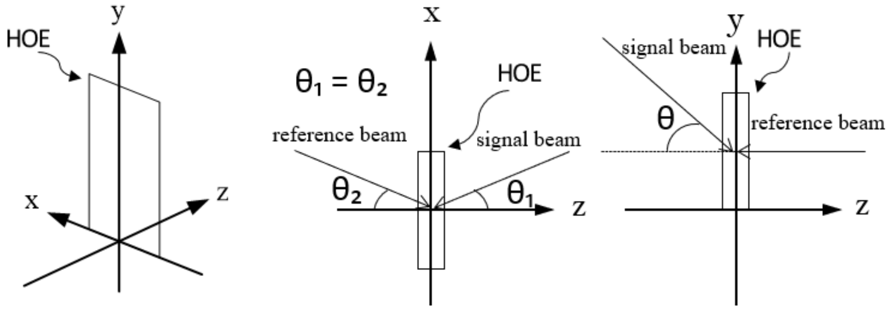


Figure 6. Detailed proposed method for eliminating overlapping images in symmetric HOE. (a) Establishing the reference three dimensions x, y, z for HOE. (b) Setting the incident angle of the reference beam and the signal beam to be the same in the x-z plane. (c) Introducing an arbitrary angle variation of the signal beam's optical path with respect to the y-axis in the y-z plane.

Fig. 7 depicts the optical system configuration for recording the proposed HOE. To fabricate the proposed HOE, a half waveplate and a polarizing beam splitter(PBS) are used to divide the beam into the signal beam and the reference beam. The PBS separates polarized light into vertical and horizontal directions, while the half waveplate adjusts the polarization state of the separated beams, allowing for rotation in the desired direction. By utilizing both the half waveplate and the PBS, the optical system can control the precise polarization state and manipulate the oscillation and propagation directions of the beam. The signal beam passes through an spatial filter(SF) and an iris to ensure a clean beam by filtering out noise. The progressed signal beam then incident onto the holographic emulsion through optical components. The reference beam passes through an SF and M1, M2 before entering the hologram emulsion. Both the signal beam and the reference beam are incident on the hologram emulsion in a symmetrical angular configuration of 65 degrees.

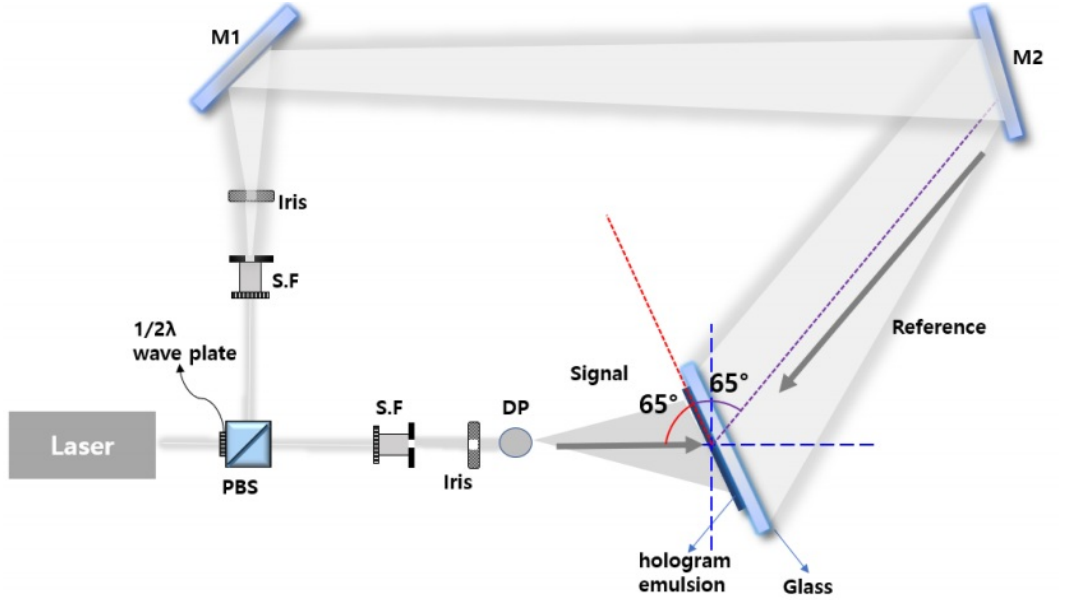


Figure 7. Optical experimental setup for recording the proposed HOE. The signal beam and the reference beam are configured symmetrically at 65 degrees.

3. EXPERIMENTAL RESULTS

Fig. 8 depicts the schematic diagram of the configuration based on the proposed method. The utilized laser has a power of 500mW and a wavelength of 532nm. The laser beam is reflected by M1 to M2. At M2, it is divided into the signal beam and the reference beam through PBS. The signal beam passes through SF and undergoes a change in the optical path through M3, M4, and a lens (f=25.4mm). Depending on the position of M4, the signal beam can vary its optical path at an arbitrary angle around the HOE's y-axis. The reference beam passes through SF and is reflected by M5. The reflected reference beam is incident on the HOE at a symmetrical angle with the signal beam, facilitated by M6.

Based on the optical experimental setup presented in Fig. 8, it is possible to fabricate the proposed HOE. The variation in the optical path of the signal beam can be achieved through the angular adjustment of M4. The fabrication of the proposed HOE is conducted in three instances. The reason for three fabrications is to observe the results corresponding to optical path variations of 10°, 20°, and 30° for the signal beam. The optically fabricated HOE are illustrated in Fig 9. Fig. 9(a) shows the HOE with a 10° optical path variation along the y-axis when viewed along the HOE x-axis. The beam power used for the fabrication in Fig. 9(a) is 100μW, with an exposure time of 120sec. Fig. 9(b) depicts the HOE with a 20° optical path variation along the y-axis when viewed along the HOE x-axis. The beam power used for the fabrication in Fig. 9(b) is 69μW, with an exposure time of 180sec. Fig. 9(c) represents the HOE with a 30° optical path variation along the y-axis when viewed along the HOE x-axis. The beam power used for the fabrication in Fig. 9(c) is 37μW, with an exposure time of 270sec. The HOE results shown in Fig. 9 contain multiple ring patterns, indicating a lack of high quality. This is attributed to the non-uniformity in beam distribution and vibration during the HOE fabrication process. However, the central portion of the fabricated HOE exhibits a uniform distribution, indicating the successful formation of the desired grating pattern in the central region. Consequently, in this experiment, the focus will be on utilizing the grating pattern in the central region. Fig. 10 illustrates the experimental setup for image reproduction using the fabricated HOE. The presented system consists of a projector, a screen, the HOE, and a camera for image acquisition.

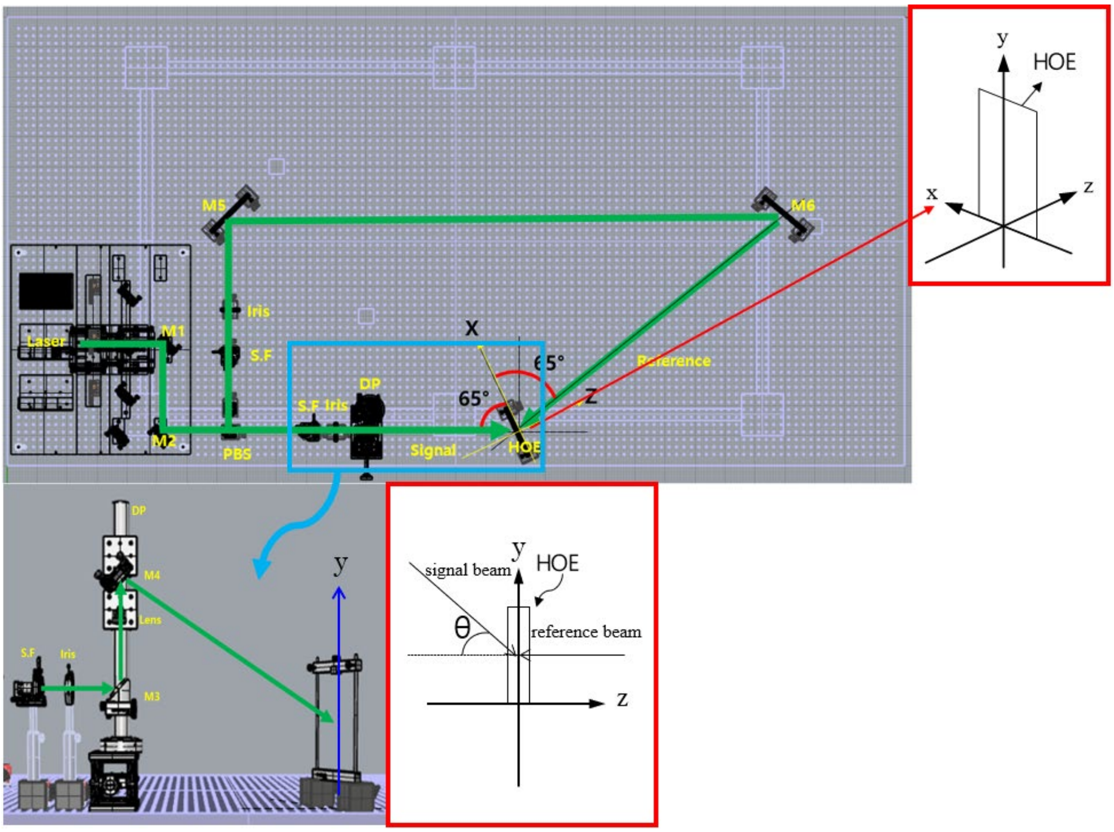
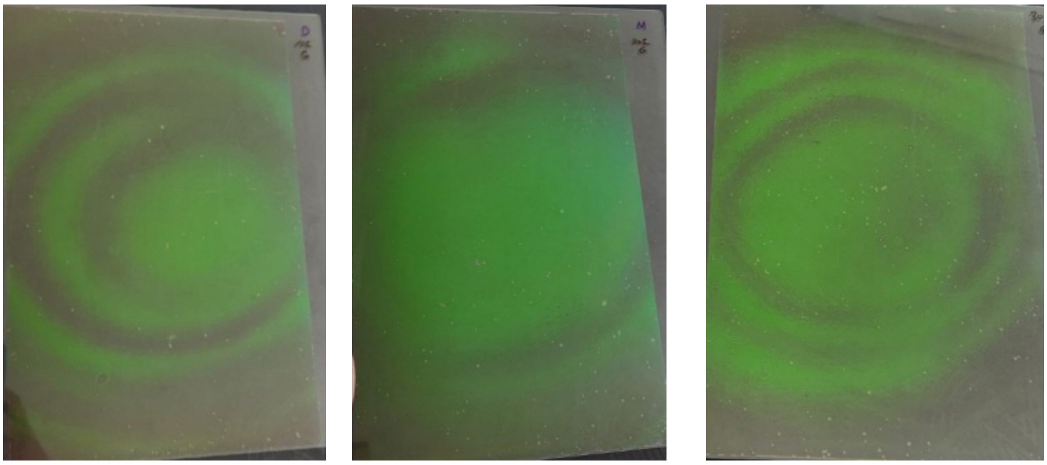


Figure 8. Experimental system configuration. The beam from the laser passes through M1 and M2, and then is split into the signal beam and the reference beam by PBS. The signal beam, through the design of the sky-blue box, utilizes DP to change the optical path of the signal beam along the y-axis of the HOE at an arbitrary angle. The signal beam and the reference beam are incident on the HOE at an equal angle of 65° in the x-z plane relative to the HOE



(a) (b) (c)

Figure 9. recorded HOEs by the proposed method. (a) recorded HOE with 10° incident angle on y-axis (b) recorded HOE with 20° incident angle on y-axis (c)) recorded HOE with 30° incident angle on y-axis

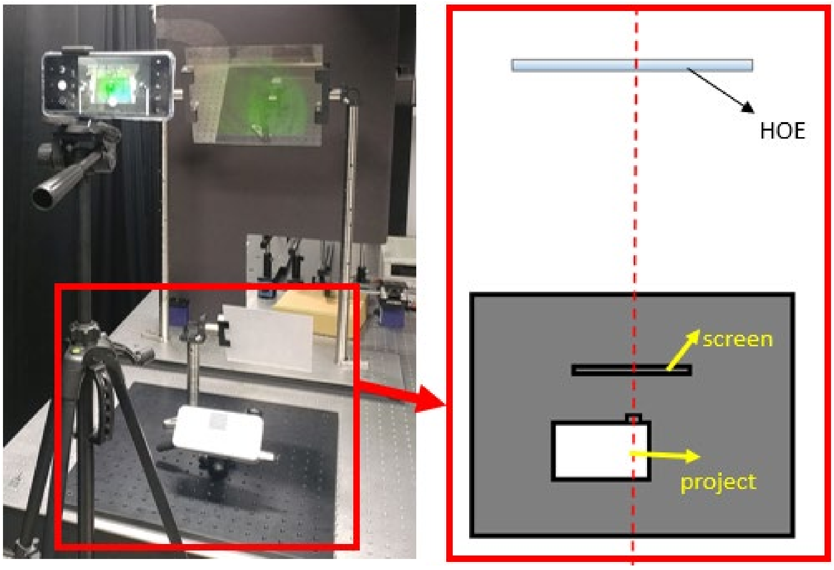
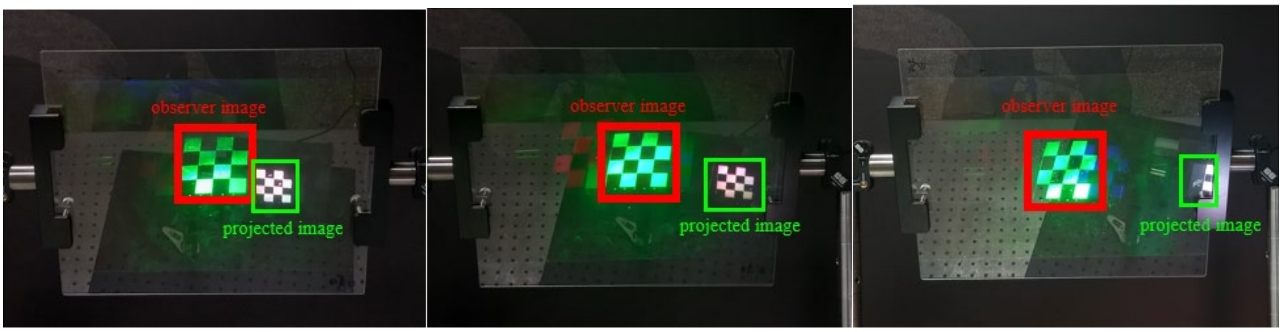


Figure 10. Experimental setup for image reproduction. It consists of a projector, screen, HOE, and a camera for image verification.

Fig. 11. Experimental results of HOEs reproduced in the provided display environment. Fig. 11(a) shows the reproduction result of Fig. 9(a) with a 10° variation in the optical path. It can be observed that the projected image and the observer image are not completely overlapped, but they are not fully eliminated. Fig. 11(b) presents the reproduction result of Fig. 9(b) with a 20° variation in the optical path. The result shows a noticeable absence of overlap between the projected image and the observer image, but it cannot be considered fully eliminated. Fig. 11(c) displays the reproduction result of Fig. 9(c) with a 30° variation in the optical path. The result demonstrates that the projected image and the observer image are not overlapped, and it can be considered that the projected image has been successfully eliminated.



(a) (b) (c)

Figure 11. Experimental images of the proposed HOEs (a) HOE 10° on y-axis. (b) HOE 20° on y-axis (c) HOE 30° on y-axis

4. CONCLUSION

In case of conventional symmetric HOE application, the HOE display system may provide a unsuitable displaying image to a observer due to the reflected image on HOE surface or other optical components. Therefore, to eliminate such effect on the HOE based display system, a modified HOE recording method is proposed. The proposed HOE is recorded and fabricated by optical system. In this experiment, three HOEs were fabricated, each with a variation of 10°, 20°, and 30° in the optical path of the signal beam. The display results show that the HOE with a 10° variation in the optical path does not show overlapping between the projected image and the observer image. Finally, it is observed that the projected image is completely eliminated in the display result of the HOE with a 30° variation in the optical path of the signal beam.

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Synthesis art and other applications of DCG holograms in display holography

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ABSTRACT

The report focuses on the various applications of holograms on dichromated gelatin (DCG) in display holography. The benefits of DCG holograms are highlighted, the most significant being their high diffraction efficiency in the blue-green range and remarkable transparency across the visible spectrum. However, DCG holograms have some drawbacks, such as a lack of sensitivity to red light, low sensitivity (compared to AgHal materials) in the blue-green region, the use of harmful isopropanol solutions during chemical-photographic processing and the need to protect holograms from environmental influences during use. Different processing modes are used depending on the intended use of DCG holograms in art. The transparency and brightness of DCG holograms made it possible to create a set of paintings referred to as "synthesis art." It is combination of painting and holography when a DCG hologram is superimposed on a painted picture and properly illuminated, constructing a three-dimensional image that added bright and three-dimensional details to the main painting. Unique properties of DCG holograms were applied to record holograms of pieces of art, to manufacture souvenirs, keyrings and to decorate items of optical glass by DCG holograms. The report includes a demonstration of the author's works with DCG holograms recorded in the Holographic department headed by Yu. Denisyuk, State Optical S. I. Vavilov Institute, St. Petersburg, Russia.

Keywords: Dichromated gelatin, DCG hologram, transparency, brightness, synthesis art, pieces of art, optical glass.

1. INTRODUCTION

Currently, there are three main types of recording media for recording pictorial holograms: silver halide, photopolymer and dichromated gelatin (DCG). They differ significantly in many parameters: general and spectral sensitivity, the method of chemical and photographic processing, the properties of the holograms recorded on them. In this case, we will talk about photographic plates, the photosensitive component of which is a layer of BHJ, which is a polymer material of animal origin. The addition of a certain amount of ammonium dichromate to this polymer makes the photographic material sensitive to the short-wave radiation spectrum. However, the sensitivity value for the blue-green range of the spectrum is about 10 times lower than that of a photopolymer, and 100 times lower than that of AgHal materials. Another feature of DCG holograms is their hygroscopicity, which requires the protection of the emulsion layer from environmental influences. Usually this is optical glue along the contour or entirely to the entire surface. DCG holograms have high (up to 99%) diffraction efficiency and exceptional transparency, and being well protected from moisture, they are durable.

There are several options for making DCG photographic plates, which are based on two methods. The first is the use of industrial silver halide photographic plates, in which all photosensitive components are chemically removed from the photo layer, leaving a pure gelatin base on the surface. Then the photographic plate is bathed in a solution of ammonium dichromate, after which it acquires photosensitivity. The second method consists in preparing a gelatin emulsion, into which ammonium dichromate is injected, followed by coating the emulsion onto clean glass. After exposure, the DCG photographic plate is immersed in water or a special solution to swell, and then follows the process of dehydration in isopropyl alcohol solutions with an increasing percentage from 25% to 100%. The processing ends by heating the hologram at a temperature of ≥ 100 ° By varying the temperature of the solutions, the processing time and the heating temperature, it is possible to obtain holograms with different characteristics. The extreme cases are shown in Fig. 1. This is either a hologram with a high diffraction efficiency (≥ 90%) and a narrow diffracted spectrum response (about up to 12 nm), or a lower DE (50-60%), but with a wide spectral response (≤100 nm). The spectral response of the processed DCG hologram usually has a spectral shift to the long-wavelength region of the spectrum. In our work, S. Soboleva manufactured DCG emulsion, coated it to the substrate by molding and processed DCG plates according to her own technology. Depending on the purpose of the hologram, one or another processing option was used.

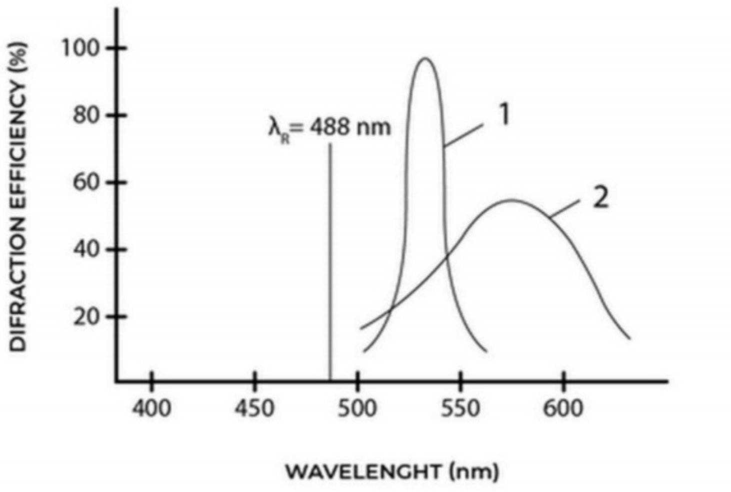

Figure 1. Diffraction efficiency of DCG holograms vs wavelength of record on different processing: 1. Very high DE, narrow spectral response, small shift and noise free; 2. Not very high DE, wide spectral response, big shift

2. DISPLAY DCG HOLOGRAMS

Taking into account the high efficiency and narrow response spectrum of DCG hologram, the holographic image turns out to be bright, noise free, with a saturated monochrome color and conveys a great depth of the scene. Having at our disposal an argon single-frequency Spectrum-Physics laser with a power of several watts, we have recorded DCG holograms with a size up to 20x28 cm at a wavelength of 488 nm. Moreover, some of them were copies of holograms (H2) from the transmission master and, accordingly, part of the image was located in front of the hologram plane.

Figure 1. 1 - "Winds of hope". A jewelry composition dedicated to the 500-th anniversary of Columbus' discovery of America. Silver, nickel silver, glass, author E. Artamonov. DCG hologram (H2), 20x28 cm. 2 - "Don Quixote". Silver figure of Don Quixote from the Kremlin Museums. DCG hologram (H2), 20x28 cm. 3 - Holographic selfie. DCG hologram (H2), 20x28 cm.

3. SYNTHESIS ART.

DCG holograms are distinguished not only by high DE, but also by exceptional transparency. Together with my colleague, physicist and amateur artist Nikita Solovyov, we decided to use this property of DCG holograms in painting to enhance the emotional perception of paintings. The idea was to complement the flat image of the painting with three-dimensional and bright holographic elements. The painting was covered with a transparent DCG hologram and, with appropriate lighting, bright, three-dimensional details appeared in the space, giving the work unusual properties. My colleague called this method of presenting artistic material "Synthesis Art". The idea itself turned out to be feasible, but from an artistic point of view, the problem arose with the choice of a plot for paintings and objects for recording holograms. It requires the imagination and talent of professional artists. Photographs of experimental paintings in the style "Synthesis Art" are in Figure 3 and Figure 4.

Figure.3. "Wall" - paintings in the style "Synthesis Art". When the painting is illuminated from a certain angle, "treasures" appear in the hole of the wall.

Figure. 4. Experimental paintings in the style of "Synthesis Art": "Redemption of sins", (28x20 cm); "Spring" (28x20 cm); "Composition 17/19" (9x12 cm); "Time" (9x12 cm).

4. DCG HOLOGRAMS AND OPTICAL GLASS.

Due to its exceptional transparency, DCG holograms are well combined with works of art made of optical glass. Artist O. Shorokhova, who specialized in the field of ceramics and glass, initiated experiments in this direction. DCG hologram with a three-dimensional image is sticked with optical glue to the surface of a polished glass product. When the light illuminates it at a certain angle, a bright three-dimensional image appears inside. The production of such objects is very laborious and costly, but the result causes positive emotions, and sometimes even a "Wow" effect. Figure 4 shows samples of optical products with DCG holograms.

Figure 4. Optical glass and DCG holograms: "Pyramid" with a Pharaoh statuette "inside" (1); “Ashtray” with a DCG hologram; "double-headed eagle" (2); DCG hologram of on the edge of the ashtray (3).

5. DCG HOLOGRAMS IN THE SOUVENIR INDUSTRY.

At the end of the last century, goods and souvenirs with DCG hologram became widespread – these are key rings, pendants, wristwatches with a cover glass in the form of a hologram, etc. We also took part in this type of activity. The consumer's attention is attracted not only by the unusual nature of the holographic image itself (its volume, brightness), but also by the object, the quality of which we attached special importance to. For example, we needed a miniature model of the coat of arms of Russia – a double-headed eagle - to make the keyring "Russia". The production of the model was carried out using thy same technology and equipment as for the manufacture of coins. Only personal participation of Yu. N. Denisyuk provided access to a special machine (the only one at the mint) and the success of the project - we received two volumetric (5 mm deep) high-quality metal models, which were used as an object for recording DCG holograms. A high-quality model for the «Moscow» key ring was produced at the art-casting factory. Works of art were also used as objects for DCG holograms, so we recorded several holograms of old Japanese netsuke figurines from a private collection. In cooperation with Y. Gentet (France, master holograms) and V. Vanin (Russia, copies) we made special souvenir for the SEXTAN AVIONIC. The object was a miniature replica of a helmet with a HUD, made on a CNC machine according to the drawings of a real helmet. Samples of products with DCG hologram in Figure 5.

Figure 5. Samples of products with DCG holograms.

TRACK 7.

Business of Holography

Holography industrialization by ZEISS microoptics

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ABSTRACT

For the industrialization of micro-optical and holographic products, e.g., holographic transparent displays, augmented-reality head-up-displays, and many more in the automotive, consumer, and hometech markets, a complete production chain has been developed and is currently in set up at Zeiss Microoptics together with our partners. We focus on volume holographic solutions due to its wavelength selectability and its suitability for mass production with the in-house developed volume holographic mass replication machines. As a fact, volume hologram manufacturers outside the security market failed so far. We at Zeiss Microoptics are aware of this challenging situation and are now facing to change it. In order to do that we set up the full development and production chain to address the above-mentioned three markets with their unique market requirements, product needs, and cost situations. As a part of Zeiss in total, we benefit of a variety of advantages to set up the industrialization chain, e.g., brand, internal funding, but also unique development capabilities and hardware resources, like for example several thousand square meters clean room areas only dedicated for the hologram master production. The master elements are an essential part of our optimized hologram replication strategy which just goes beyond fabricating masters and then replicate them with your replication machines 1:1. Doing so, an optimized chain has been set up, so that in the end the replicated holograms can be integrated into the customers' products. On our development way, we at Zeiss Microoptics created an already big and still increasing IP portfolio and bear an extensive know-how in all aspects of the chain, e.g., optical design, mastering, replication, and integration. As indicated in the beginning of this abstract, we face the challenge not alone but also cooperate with distinctive strategic partners which include their unique solutions and we also connect them strategically where necessary, e.g., machinery, special light tools, holographic materials, and more into this unique ZEISS Microoptics Enabling Ecosystem industrialization chain for mass fabrication. Only by combining the respective unique selling points of each partner such an industrialization chain will be successful. In this article, we will describe all parts of such an industrial ecosystem, machinery developed within it, as well as present some holograms developed there, mainly for automotive industry needs.

Keywords: Volume hologram, hologram mastering, hologram replication, HUD, industrial, automotive

1. INTRODUCTION

The holography has a long history since the first hologram made by Denis Gabor in 1948[1,2]. The laser invented a few years later, was the first boost to think and develop about technical solutions for potential holograms applications for consumer markets [3]. In 1974 Michael Foster [4] introduced a method for duplicating holograms mechanically by an embossing process similar to that used for stamping of compact discs. By this, transmission surface hologram replication has been enabled which is used in textbooks, art publications, publicity handouts, on credit cards, ID cards and banknotes as security devices, if they have been converted to reflection holograms by an aluminum foil backing.

In the case of volume holograms for imaging applications, quite a lot of them have been mastered for art purposes [5]. However, mass production of volume holograms in noticeable quantities and bigger formats was not possible for a long time for many technical reasons. The main reason was the lack of color photomaterials withstanding environmental changes and lasers suitable for such materials' exposure. By overcoming these issues in order to enable an industrial replication of holograms, distinct developments have been done in the field of photopolymer materials [6, 7, 8], software solutions for the optical design [9], tunable laser systems enabling RGB-mastering solutions [10, 11, 12], roll-to-roll

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volume holographic replication machines [13, 14, 15], and our, currently in development, multiple integration solutions for different markets and products. Some of them are discussed below in the present article.

With all this progress in hardware and software, we at ZEISS Microoptics are able to overcome the past and current restrictions and revolutionize the current holography market landscape from being focused on mainly artistic or museum artefact representations [16], surface and volume holograms for banknotes [17] and the latest attempts for AR/VR-googles based on volume holograms [18].

However, nearly all the applications which can be imagined can also be realized with more or less classical optical systems. The properties of catadioptric systems containing lenses and mirrors can be described analytically and numerically. Optic simulation tools are fully developed and in the fabrication chain nowadays, whereas polishing the last atomic layers from optical surfaces is the last remaining challenge. In the end, major improvements for applications like binoculars, magnifying glasses and even Head-Up-Displays based on catadioptric systems are not expected anymore.

As for one example, the size of the virtual image and the viewing distance to the virtual image – the field of view – define the necessary installation space for a head-up-display-system under the dashboard of a car, whereas the installation space is determined by the strategy applied of how to fold the optical path, so that a desired virtual image distance is achieved. So-far no holograms are necessary for such a kind of device, but also the minimum volumetric size is then defined without a real possibility to shrink it.

We at ZEISS Microoptics analyzed the product needs and current restrictions of past and existent HUD-devices in-depth and identified that the unique-selling-point of being able to set up an augmented reality HUD system is the drastic reduction of the installation space. New and advanced hybrid -classical and volume holographic – systems offer such an opportunity. These hybrid system approaches are defined by a clever combination of the best solutions given from both worlds and by this, we realized AR-HUD systems with volume needs of below 10 liters for given direct automotive requirement charts. Other application examples are holographic transparent displays, holographic button configurations, lighting applications, and transparent holographic detection or camera systems. Although some could be realized in a classical way, most of them can only be realized with micro-optical, volume holographic, or hybrid systems.

Actually, to the classic optical toolbox we are adding a completely new toolbox – industrial-ready holography.

2. VOLUME HOLOGRAMS PRODUCTION CHAIN

In this chapter, we refer to our efforts and solutions in the field production chain optimizations and in more details about the original manufacturing – mastering – and the replication of these. Further aspects are given in our own literature for the optical design [to be published during the 2023 SPIE Digital Optical Technologies (EDO23): Advanced multilayer holographic technology for the realization of compact AR-HUDs, 13] and planned future publications.

2.1 Production chain optimization

In the past attempts to realize a product based on holography failed due to the lack of appropriate system technologies beside the holography itself. Further, the required optimization between the different important hologram set up phases could not be done, due to the large entree barriers (financial, logistic, technological, …). Furthermore, we believe that at least a combination of micro-optical and holographic units are required to have an industrially realizable product with holographic features.

However, we at ZEISS linked the missing dots, optimized the interfaces, and based on this, developed completely new solutions for this optimized production chain. But as always, optimization relies on the final products which have to be addressed properly for the different markets. We at ZEISS Microoptics focus on the markets needs for the automotive, hometech, and consumer markets. For example, a head-up-display has completely other constraints for automotive than a similar function product for the consumer market.

Our optimized production chain consists of the following parts:

- Optimized optic design with respect to the production chain and the needs of the final application

- Therefore, a deep knowledge of the recording photopolymer properties is a necessity (Sellmeier coefficient, Young's modulus, etc.)
- Availability of a stable self-developing material - ZEISS has access to several photopolymers
- Origination process for the master hologram – ZEISS has more than 45yrs experience in holography
- Replication machines ready for mass production – a roll to roll process or a roll to sheet process assures the mass production
- Quality assurance and measurement equipment to quantify the optical properties of the HOE
- Understanding of the encapsulating process of the HOE in the final product, for example optical bonding or injection molding

A visual representation of the production chain is given in Figure 1. In the next chapter we will discuss our mastering and replication parts of the production chain.

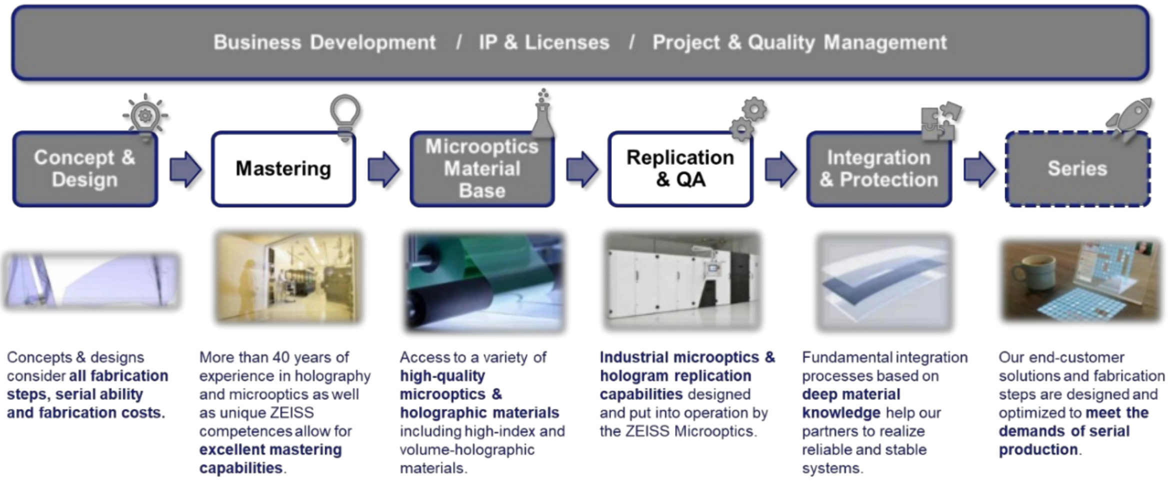


Figure 1. ZEISS Microoptics production chain.

2.2 Realization of a series production with masters and replication machines

For the origination process there exist two main approaches to produce the master hologram - analog and digital. For digital mastering, we are using a digital holographic printing process like the one introduced in Yamaguchi article on that topic [19]. With digital mastering typically rapid prototyping samples and all lighting and button samples can be produced. However, the main difference between analog and digital mastering, with respect to the optical performance is that digital mastering yields pixelated holograms, therefore analog mastering still seems advantageous for see-through applications. But for both processes, it is necessary to have access to high quality optics and coatings, which are provided to us by ZEISS in-house.

Next challenge is the availability of clean rooms and climate-controlled stable environment. To face this challenge, ZEISS has set up specially dedicated clean rooms (>2000 m² and rising) and respective holography adapted optical setups which are mandatory for the stability of the holographic mastering. The labs are of course built on the ground based on rocks to have the best starting conditions for mechanical stabilization. Thus, the needed stability and also a controlled temperature environment are achieved. Due to its unique location, further passive and active mechanical stabilization techniques, and highly precise lab temperature monitoring and control, we are able to achieve conditions necessary for best quality holograms origination.

Figure 2. Exemplary inside view in our ZEISS Microoptics mastering labs.

All the mastering set-ups are customer-specific, separated partly into different clean rooms as necessary to fulfill the product needs, and to enable a semi-automated procedure with minimal tooling in-between. However, such a hologram mastering production will stay at least for a foreseeable timeframe at a lot-size of 1-100, maybe 1000 samples per year. That also determines a later entrance barrier for mass production as these typically require lot sizes in the magnitudes 100,000 and more.

This is solved by our developed volume-hologram replication machines. To mass-produce the different hologram types, and to assure highest quality standards, several different replication machines have been developed in the last decade. We cluster currently into machines for free-space-, edge-lit- and waveguide - hologram replication. Mostly in all the cases the replication process is set up so that holograms for non-flat and partially curved substrates, e.g., automotive windshields, can be illuminated for the replication on the on flat surface. In order to be able to achieve the required replication yield, we decided to focus on roll-to-roll replication machinery, so the photopolymer material is also supplied to us in rolls. During the functionalization – hologram replication from the master into the photomaterial – several effects can be observed, depending on the respective set up and the hologram to be replicated. Typically, we have to compensate the photopolymer shrinkage by the laser wavelengths during replication of up to 20nm at a material dependent shrinkage of the photopolymer of up to 1-2 % shift, so that the masters' maximum diffraction efficiency and later product wavelengths are matched. This aspect has been a long-time entrance barrier for mass production as the holography techniques could not match the requested and exact colors of the customers brands. For arts purposes it does not matter, but it does for the brands owners.

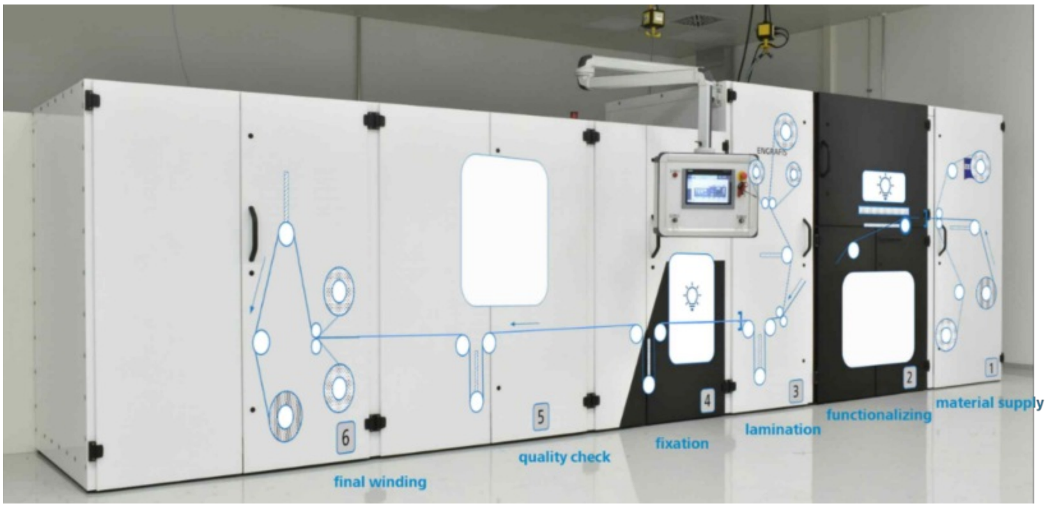


Figure 3. Photograph of our free-space volume hologram replication machine with an overlay explaining the basic steps of the replication process

Surpassing this challenge, the next one is that the automotive market requires 100% quality control of each produced item, therefore inline measurement setups had to be developed and included into the machines. Further, the installed bleaching process in the optical replication machines is optimized to assure the maximum transparency and minimal haze requirements for the market and product requirements.

Our replicator machinery is based on different modules, so we can choose between a roll output or a sheet output for a better hand-over to the following production processes. In detail and uppermost importance this also defines the following integration processes for the final products. We support our partners with integration consulting for different processes and how they have to deal with the replicated holograms so that an optimized product can reach their market.

2.3 industrial ecosystem

As mentioned, several crucial system technologies in combination with our production chain are required for the full chain – a whole ecosystem is needed. In the last decade ZEISS Microoptics has identified the best partners for lasers for mastering and replication, special purpose machinery, and photopolymer and process materials to make sure that there is a landscape of suppliers ready for the series mass production. These contained beneath other, the fixing of the photopolymer materials, the development of laser systems adapted for holography, and an implementation of a quality management.

A strategic partnership with a unique solution and product provider with a constant supply of materials in the series is a must. Such an ecosystem has been set up by ZEISS Microoptics as this has to exist before a nomination for a series product.

Our ecosystem, as shown in Figure 4, consists of strategic suppliers, which share their know-how and production capacities with this chain, e.g., a necessary cover foil during edge-lit replication or adapted rolls for the replication machinery. Further, we work together with strategic partners who share their knowledge, production capacities, and also develop unique solutions which are or have not been available before. There we are in a close exchange of holography needs so that the developed solution matches exactly the chain needs, here for one example are the laser systems which were specially developed for our needs. Furthermore, we have built-up the interface between the different ecosystem partners and consult them so that the development of the whole ecosystem for the complete industrialization of the hologram replication is target oriented. Yet on the other hand, we reduce the time-to-market for this new technology to a minimum. And finally, we are glad to mention that such a whole manufacturing chain has been built up, for the first ongoing series of development projects with soon start of production dates.

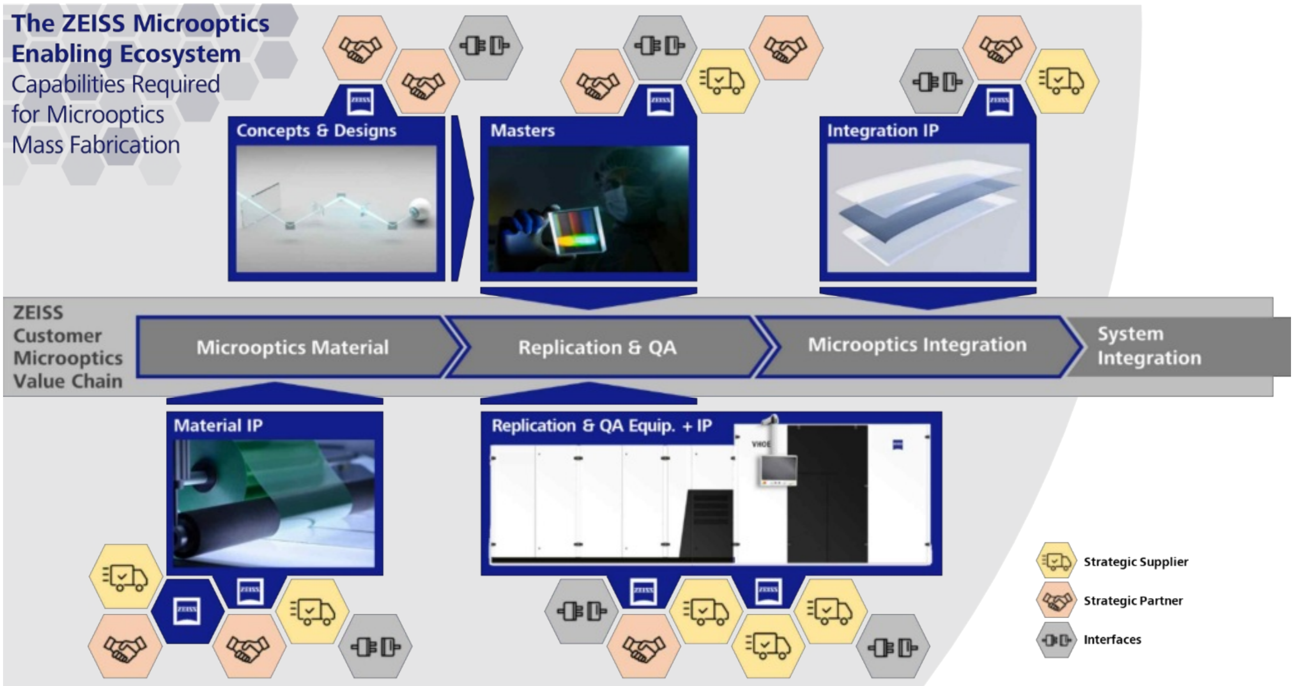


Figure 4. ZEISS Microoptics Enabling Ecosystem with capabilities required for the mass fabrication

3. VOLUME HOLOGRAMS FOR AUTOMOTIVE INDUSTRIES

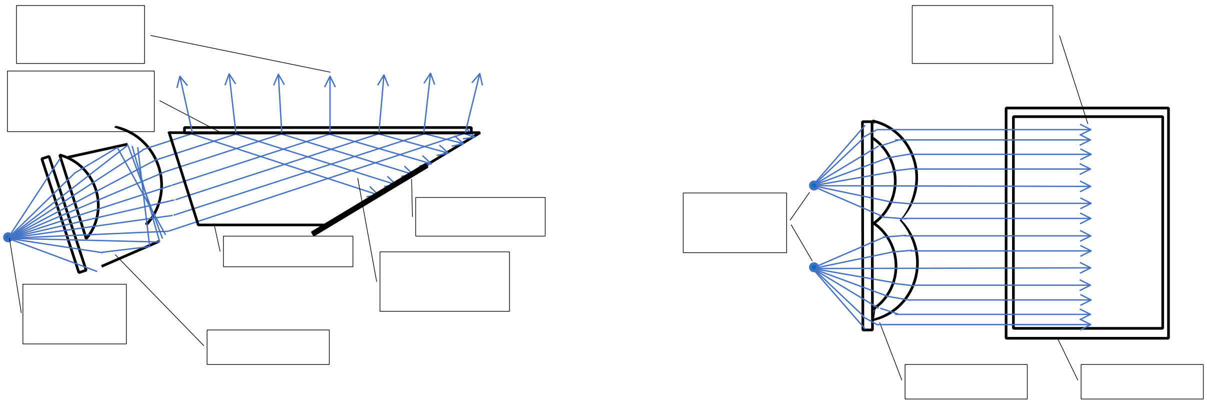
With all the capabilities within our ZEISS Microoptics Enabling Ecosystem, we have developed product solutions beyond the "simple" usage of holograms to prevent counterfeiting. Here, we will present some examples of our cooperations with our product partners from the automotive industry. By using the word "holograms" in this article, we refer to them for displaying certain images, as well as holograms acting as holographic optical elements, which are able to realize one or multiple optical functions.

3.1 Motorbike backlight

In principle diffractive lighting elements are already known for vehicles. However, holographic solutions can do more than only illuminating as classical lighting elements are also doing. Holograms can create a three-dimensional warning function, where a greater observers' awareness is postulated in comparison to that of a classic warning light, which in the end will increase the safety of all road user but especially of the vulnerable road users. With the holograms, we can assure an optically larger vehicle so that a larger and safer distance is stimulated for the bigger vehicle's driver. The solution could be a three-dimensional image visible at a certain distance behind the motorbike.

The main challenge of such a holographic backlight is the limited available space for its realization. For most hologram image reconstruction setups, it is beneficial to use an approximately planar light wave which illuminates a finite hologram active area und suppresses at the same time the 0th order of the hologram illumination. These requirements contradict the need for compact design of a hologram lighting device. At the same time, such a compact design is necessary for a large number of automotive applications.

Addressing these challenges, our solution is to illuminate the replicated hologram element with a lightguide, whereas the element is recorded in such a way that its illuminating light angle is equal to the lightguide's total internal reflection angle. By this, we suppress the 0th order by catching it in the dumper and do not distract the viewer (road user). At the same time the whole device is compact enough to be used as a motorbike backlight [20]. Figure 5(a) depicts a principal scheme of such a device designed specifically as a transmission hologram. In detail, the light in this case is collimated by a classical collimator and is in-coupled into a lightguide having the form of a straight prism. Further, its base is a non-rectangular triangle with a truncated tip. With other geometrical boundary conditions, a similar set-up can be realized with a reflection hologram having the advantage of being more wavelength-selective yielding a set-up for the backlight signals with strictly defined colors [21]. In another alternative set-up the light beam can be collimated with a plastic lens integrated into the lightguide, or further this optical function can be realized again with a hologram element.



(a) (b)

Figure 5. Hologram lighting through lightguide with zero order dumping. (a) – principal schematics for transmission hologram lighting. (b) principal schematics for transmission hologram lighting from two light sources (top view).

The above-described set-up, as shown in Figure 5(a), can act as a standard engineering block. By combining two or more of the engineering blocks larger holographic areas can be realized as depicted in Figure 5(b) with two light sources. The prototype of the motorbike backlight as partly described above by the reflection holograms which are illuminated by two light sources is shown in Figure 6.

Figure 6. Photograph of the prototype motorbike backlight. Realized with a lightguide with zero order dumping.

3.2 Holographic Access Control

A Holographic Access Control system with additional system features is able to provide a second security level authentication [22]. For this system realization, we utilize the interchangeability principle of light paths, where we change the direction of the light signal processing for imaging and displaying. Nowadays, even in mobile phones a two levels authentication process is used by implementing face or fingerprint recognition. We can ensure a second security level by implementing a transparent, mostly invisible holographic camera set-up to detect legitimate access.

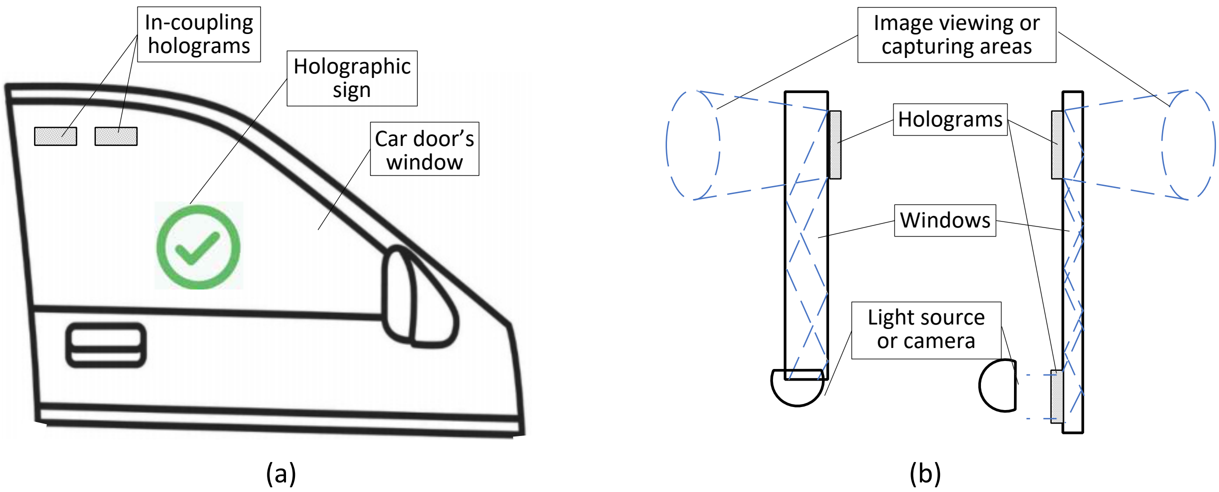


Figure 7. Holographic access control: (a) possible system installation in a door of a car; (b) window as lightguide to transfer an image in-coupled by the hologram to the camera sensor, or transfer light from the light source to illuminate hologram

Holograms for this application are recorded with the reference beam angle equal to the total internal reflection angle of the window. Such a hologram attached to the window can act as a video camera lens' hood/shade through which the image of an object placed in front of the window will be in-coupled into the window and then, because of total internal reflection effect, will pass within the window to the direction of reference beam used for the hologram recording. The interchangeability principle of light sources and camera sensors seems to be obvious, but only Zeiss Microoptics sought-after possibilities to implement it into security applications [23]. If the window is thick enough, a video camera sensor can be placed directly at the edge of it. Alternatively, the image can be taken out from the window by another similarly recorded hologram. In such a way a video can be captured and used as a second authentication factor. Alternatively, such an arrangement can be employed as an "invisible" security camera – commonly used security cameras are usually visible and as such can be easily disabled by perpetrators, whereas cameras employing holograms as camera's hood/shade do not have such a disadvantage. Moreover, if two pairs of such holograms are used in conjunction with two video camera sensors, a stream of stereo pair images can be captured and processed with face recognition software to allow or deny access to the premises. And yet, a third hologram pair attached to the same window in conjunction with two light sources can act as an indicator if access to the premises is granted or denied.

In Figure 7 (a) we show an exemplary set-up of such a second level authentication system installed into the car's window Light in-coupling holograms transfer the image stream from the outside of the car to the security system cameras, whereas the security system processor evaluates the second level authentication. If the authentication is successful, then the holographic indicator lightens up and the car doors can be opened. Figure 7(b) depicts the interchangeability principle of light sources and cameras for micro-optical and holographic set-ups, as described above. Further application examples for our security access solutions are shown in Figure 8.

(a) (b)

Figure 8. Examples of possible holographic camera implementations for access control devices: (a) working place entrance; (b) airport.

3.3 Holographic button – holographic touchless solution

As shown above, holographic set-ups can be realized with light paths in different directions. In one configuration light from e.g., a LED is delivered to e.g., an image hologram or in the other way light from the outside is coupled-in via a hologram and then delivered to an imaging sensor, realizing a camera setup. The next example will show how we combine both described light path features into one compact holographic device which can act as a holographic button – a holographic touchless solution. Such an element can visualize a 3D image of a button or another control element. If a user "touches" the 3D image of the button, the device recognizes this gesture and sends a signal to the device controls' [24].

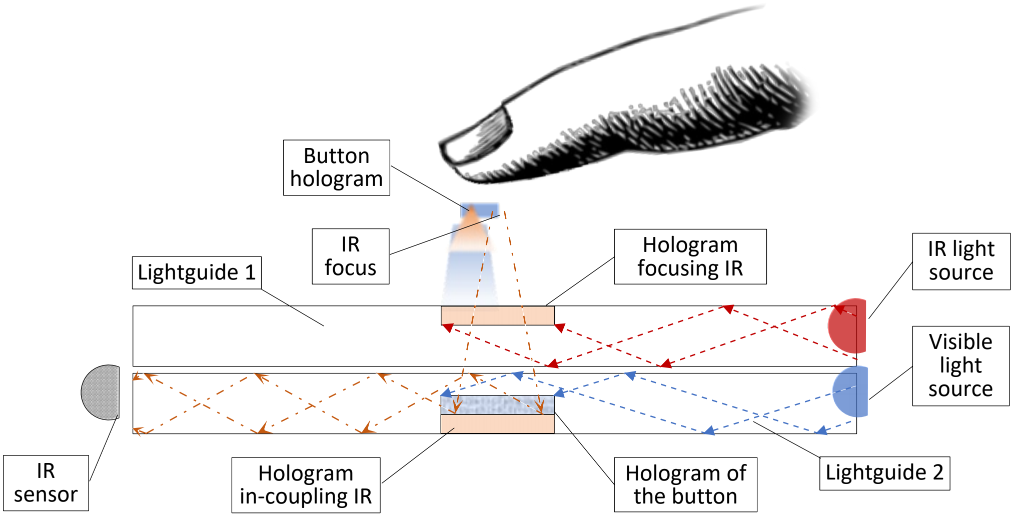


Figure 9. Holographic button' working principle.

Figure 9 shows the schematics of such a holographic touchless element. The element consists of two lightguides, three holograms, two light sources, and one optically triggered sensor. The element's configuration presented here illustrates its working principle, and of course can be modified/simplified to employ only one hologram, not reducing element's functionality.

The light from the IR light source with a wavelength range around 750-900nm is in-coupled into Lightguide 1, where it propagates due to total internal reflection towards the hologram element responsible for focusing the IR radiation. Underneath Lightguide 1 lays Lightguide 2. The light source with a wavelength range in the visible regime of 440-660nm is in-coupled into Lightguide 1, where it propagates due to total internal reflection towards the hologram element responsible for displaying the button. The holographic image of the button is displayed through the Lightguide 1 and through the hologram element responsible for focusing the IR radiation, which means the 3D image of the button is displayed at the same place in the space where IR radiation is focused.

When the user's finger "touches" the holographic button, the IR radiation is scattered back towards the lightguides sandwich device and is in-coupled by the third hologram, shown in Figure 9, to be sent within the Lightguide 2 towards the IR sensor. We utilized reflection-type holograms for in-coupling the IR radiation and out-coupling the image of the button and one transmission-type hologram for focusing the IR radiation, but of course other combinations are also possible. All holograms are recorded on proprietary photopolymer materials.

Figure 10 shows a photograph of a holographic button demonstrator employing the general working principle described above.

Figure 10. Photograph of the working holographic operating element.

4. FINAL REMARKS

The industrialization of micro-optical and holographic products, e.g., holographic transparent displays, augmented-reality head-up-displays, and many more in the automotive, consumer, and hometech markets, require a complete production chain, which has been developed and set up by Zeiss Microoptics together with our partners. We focus on volume holographic solutions due to their suitability for mass production with the in-house developed volume holographic mass replication machines. Within our developments, we at Zeiss Microoptics have created an already big and still increasing IP portfolio and bear an extensive know-how in all aspects of the chain, e.g., optical design, mastering, replication, and integration. Our ecosystem consists of strategic suppliers, strategic partners and we have built-up the interface between the different ecosystem partners, and we consult them so that the development of the whole ecosystem for the complete industrialization of the hologram replication is target oriented. We highlighted three applications which are realized within our production chain and ecosystem for mass fabrication: backlight for motorbikes holographic access control, and holographic touchless solutions. And finally, we are glad to mention that such a whole manufacturing chain has been built up for the first ongoing series development projects with soon start of production dates.

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EXHIBITION TRACK

Hologram Exhibition

[Exhibition-Oral] ISDH2023-0246

John Klayer
Independent Holographer

SPELEOHOLOGRAPHY

John Klayer

1. INTRODUCTION

- This paper chronicles the author's continuing efforts in speoholography - the making of cave formation holograms, a word derived from the combination the prefix speleo for cave and holography. He built several apparatuses using both conventional optics and multimode fiber optics. Larger diameter multimode fibers have been tested in a simulated cave environment with excellent results.

2. EARLIER WORK

- Earlier work was based on a C315M DPSS laser which required a heavy set of batteries. The apparatus using conventional optics was somewhat large and cumbersome[1], Attempts were made to reduce the size of the unit using a simple 1 mm multimode fiber to direct the reference beam and eliminate the need for a spatial filter[2,3]. Some devices were made with the hologram platen remote from the laser by lengths of fiber up to 15 meters.

Figure 1. This conventional optics contraption incorporates all the components of an ordinary holography lab including a spatial filter.

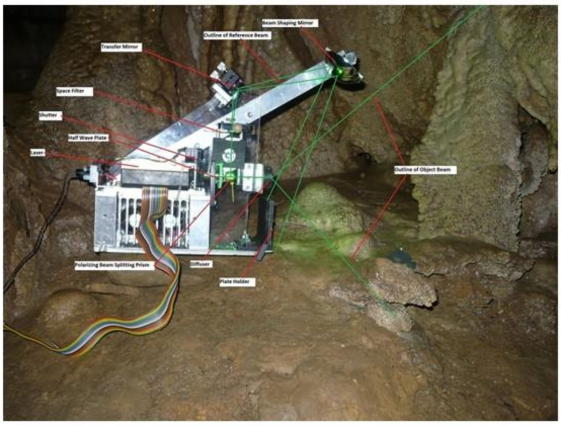

Figure 2. This is an example of a C315M device using a 1mm fiber and a convex mirror in place of a spatial filter.

Figure 3. A setup with the holography head separated from the laser with fibers carrying the reference and object light.

Figure 4. A typical cave transmission hologram made with a C315M laser reconstructed with a 594nm HeNe laser.

3. RECENT WORK

- A PL530 laser was substituted for the C315M to reduce the size and weight. In one setup a spatial filter was used to ensure a clean reference beam. A convex mirror was put in the reference beam to make it diverge enough to adequately cover the plate. Another setup used a 1 mm fiber instead of a spatial filter. The PL530 has an internal heater for the frequency doubler that requires very fine adjustment. The rest of the unit needs a TEC and well-designed feedback mechanism for stable operation. Several circuits have been tried.

Figure 5. This device, like the apparatus of figure 1, has all the basic components of an ordinary holography lab but in a smaller package made possible by the much smaller PL530 laser. The unusual, sloped platform holding the laser, variable beamsplitter and spatial filter is to minimize the number of mirrors needed to direct the reference beam. A rod extends under the laser to adjust the z axis of the space filter.

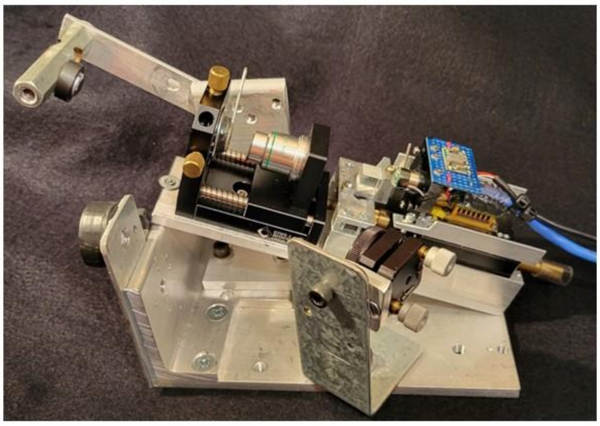

Figure 6. This PL530 device uses a 1 mm fiber to direct the reference beam and eliminate the spatial filter. The variable beamsplitter was replaced with a fixed ratio beamsplitter to further simplify it.

4. PRESENT WORK

- It has been posted on the facebook holography forum that the output of larger core fibers rival that of a spatial filter, 3mm diameter being optimum[4]. My present efforts therefore are based on 3mm fibers.

Figure 7. The output of a 3mm fiber has a few artifacts but is clean enough to be used for a reference beam.

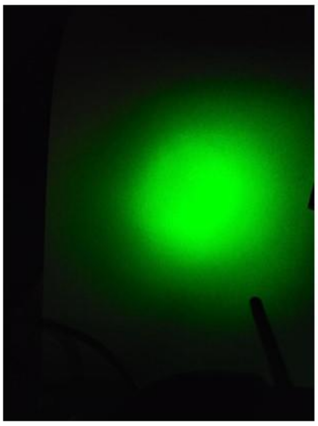

Figure 8. Short 3mm fibers maintain some polarization as indicated by the two faint dark triangular projections after passing through the axis finder in the foreground. The polarization axis can be rotated by twisting the fiber.

Figure 9. The fibers have larger diameters than the laser beam, they are therefore easily coupled. Each fiber is attached to a magnet that can slide around until the maximum output is found at the other end of the fiber. Pictured here is a PL530 laser aiming through a half wave plate to a polarizing beamsplitter and then to the object and reference fibers.

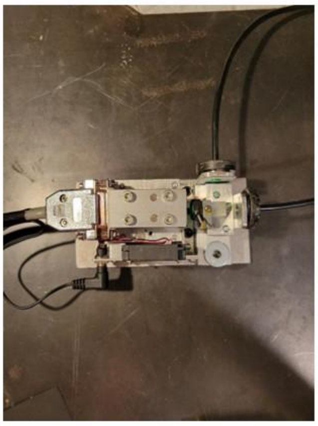

Figure 10. This is an experimental setup using a PL530 laser and 3mm fibers with a pile of rocks in the lab to simulate a cave environment. The reference beam bounces off a flat mirror and down to the plate. The object light is spread by a diffuser located at the top of the apparatus.

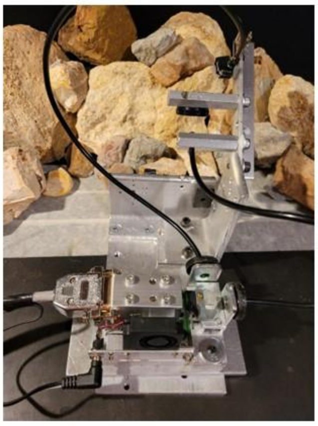

Figure 11. This is the resulting hologram from the setup shown in figure 10. It is reconstructed with a green laser diode.

5. FUTURE WORK

Given the satisfactory results of using the larger core fibers for both the reference and object beams, all my future works will probably use them.

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[Exhibition-Oral] ISDH2023-0298

Setsuko Ishii
Independent Artist

Exhibition works

Photon drawing series

Setsuko ISHII
Independent Artist

ISDH 2023 Korea

Photon drawing series

Back ground

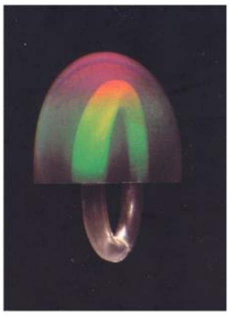
What is the attractive characteristics?

- Three dimensional image
- Color of Light

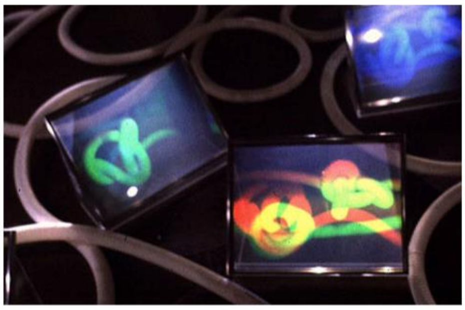
Three dimensional image

Rainbow hologram

Image from Real object



Encounter



Work N

Color of Light

Multicolor rainbow hologram

Image from Real object

Sous la Mer

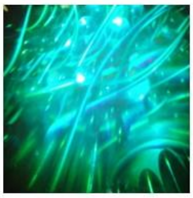
Still Alive Cypress

Still Alive Ginkgo

Color of Light

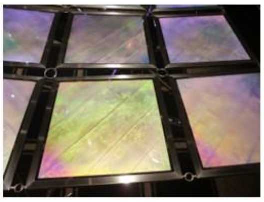
DCG reflection hologram

Image from Real object



Eternal Procession

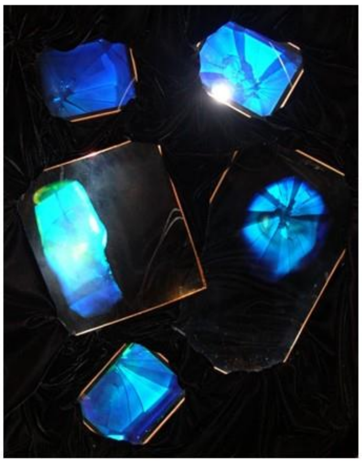
Pseudo Plane



Color of Light

DCG Reflection hologram

Image from Real object

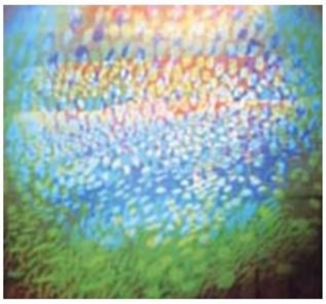


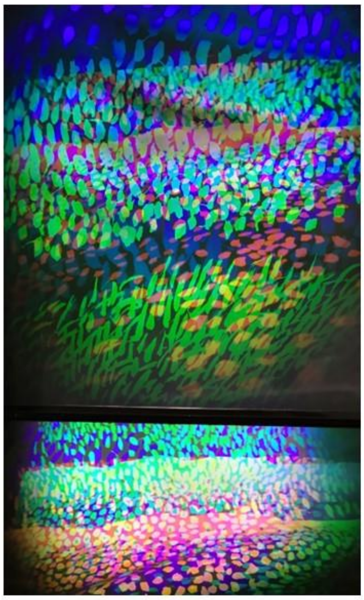
Papillon Blue

Photon drawing series

Multicolor rainbow hologram
Image from Brushstrokes

First works
Made for
Exhibition "Homage Van Gogh"
1990 the Centennial of his death





Distorted Air

Photon drawing series

Multicolor rainbow hologram

Image from Brushstrokes

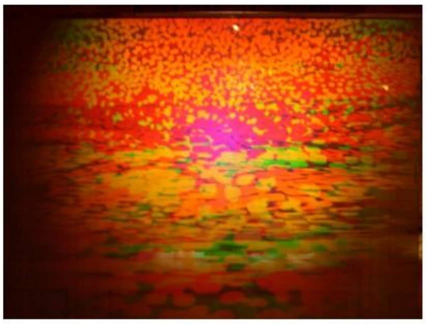
60cm×25cm each

110cm diameter

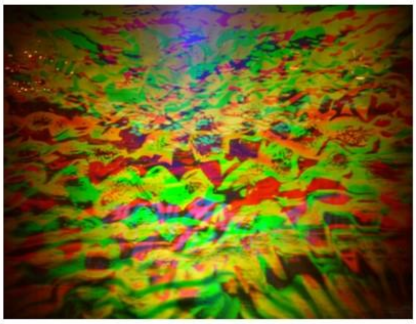
Photon drawing series

Multicolor rainbow hologram

Image from Brushstrokes



110cm×130㎝



110cm×130㎝

Photon drawing series

DCG reflection hologram

Image from Brushstrokes

Careless Lesson A 40cm×35㎝ each

Careless Lesson B

Photon drawing series

DCG reflection hologram

Image from Brushstrokes

Clock without Hands Ⅱ

As you like

Exhibition works

Photon drawing series R

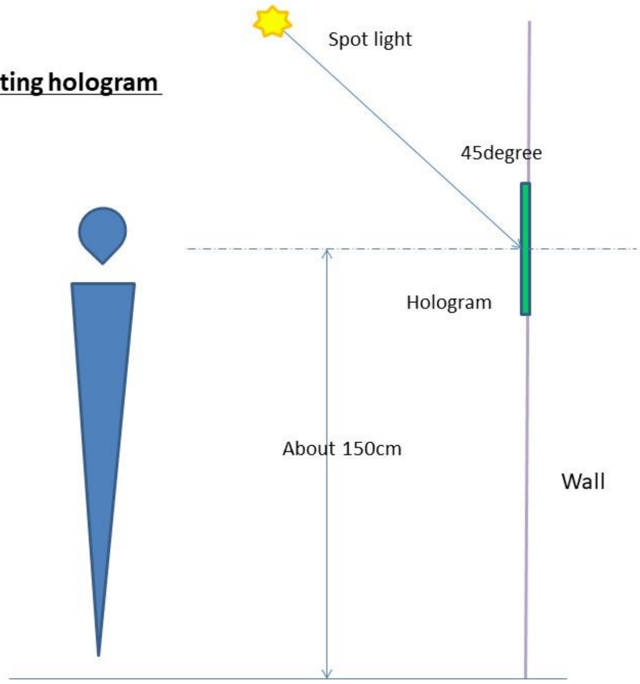
DCG reflection hologram

Image from Brushstrokes

Backside
Ink drawing
on Japanese paper

40cm × 35cm

Diagram of setting hologram



[Exhibition-Oral] ISDH2023-0310

Pearl V. John
Southampton University, De Montfort University

University of Southampton

University of Southampton

Holography at the science festival: engaging audiences with art and scientific research

Pearl John Public Engagement Leader, Physics and Astronomy, and visiting Post Doctoral Researcher, De Montfort University, UK.

June 2023

University of Southampton

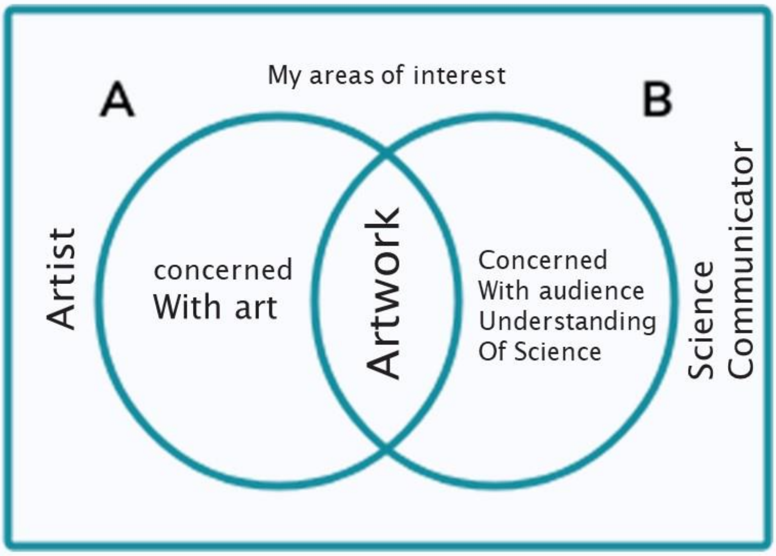
Introduction

- An introduction to my roles – Artist and Science Communicator
- The Art exhibit context
  - The Southampton Science and Engineering Festival (SOTSEF)
- The Science engaged with
- The Holographic Artwork
  - Technique employed
- Can art be employed successfully as a vehicle for science communication in a Festival?

3

University of Southampton

Art and Science Communication



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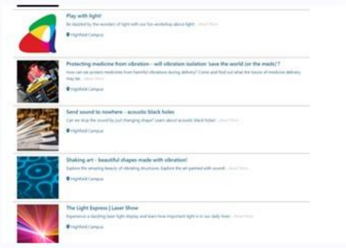
Art Exhibit Context: The Science Festival



Southampton Science and Engineering Festival (SOTSEF) is the University's annual award-winning interdisciplinary science festival that allows everyone to explore and discover what the world of Science, Technology, Engineering, Arts and Mathematics:

4,000+ visitors attend of all ages
100+ stands and shows
Holograms in talks, demonstrations and artwork.

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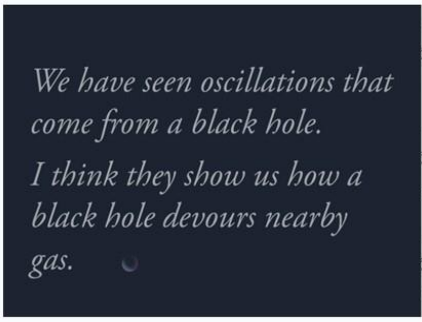
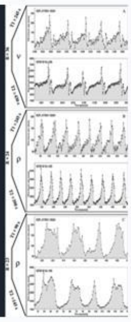
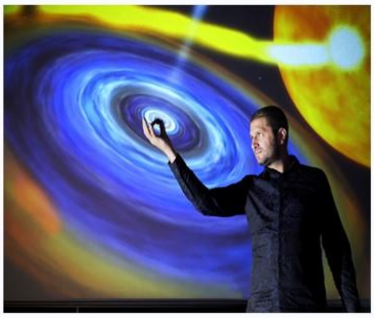
Black Holes – The Scientific Research.







Professor Diego Altamirano and his research
with Black Holes and Neutron Stars

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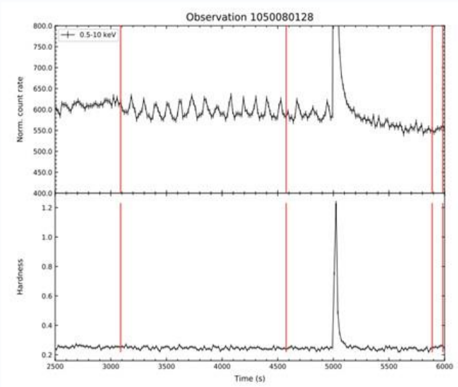
Black Holes – The Scientific Research.

And this is the 'clock' that tells you that an explosion is coming.

Where the line goes up – that is neutron star on fire.

And where the line goes down – that's the neutron star cooling down.



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The Artwork

Black Hole, 10 x 8" Mixed media, reflection hologram, Pearl John 2022

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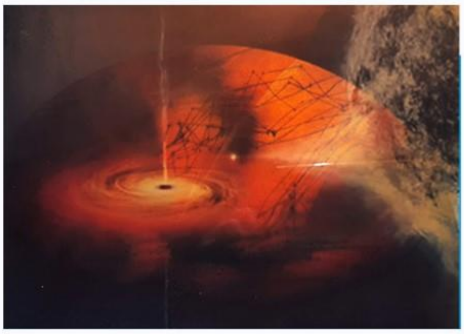
The Artwork: Details



Black Hole, 10 x 8" Mixed media, reflection hologram, from 2 viewpoints. Pearl John 2022

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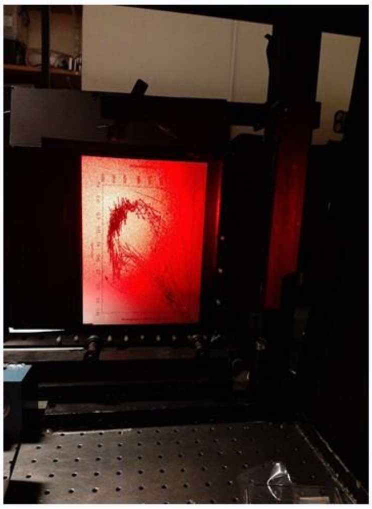
The Technique employed

- Reflection shadowgram
- 30mW Laser
- Vintage Agfa Film
- Object = photocopy of research onto on Bi-refringent acetate
- Transparent hologram interleaved with digital photograph of an illustration of Cygnus X1. NASA, M. Weiss, CXC, 2017.
- Displayed on Holixica tripod.



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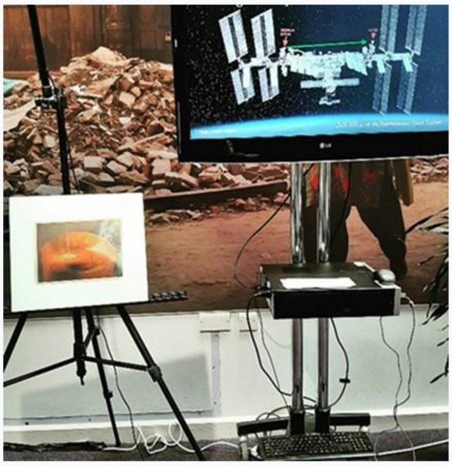
Science Communication

- Method
- Key messages
- Evaluation of Impact
- When is using an artwork unhelpful?
- Recommendations



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How do we know an audience has engaged?

- Gesturing - pointing
- Questioning
- Commenting - relating information to their own experience
- Showing and engaging others

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The ‘Impact’ of a Holographic Work of Art?

- Impact in UK Public Engagement = number of people engaged and the significance of the interaction.

- How many people saw the artwork?
- ~ 200
- What did they learn from it?
- What did they think and feel about it?

Illustration by AI Android App ‘Imagine’ P. John 2023.

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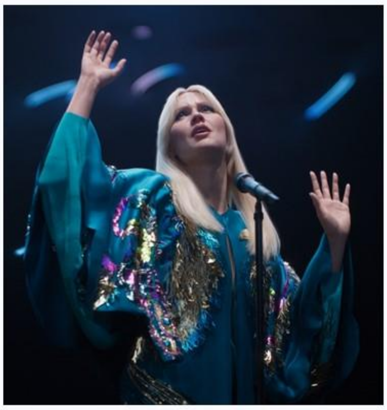
When is using holographic artwork detrimental to engaging audiences with research?

- Explaining “Fauxlography” (Not holography) to audiences.



https://www.mirror.co.uk/3am/celebrity-news/what-abba-voyage-how-hologram-27079797

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Conclusion

- Using artwork for engaging audiences at a science festival helps to form visitor experience of the event. Captures attention, engages at a deep level,
- It is recommended to have an Explainer accompany the artwork
- To evaluate audience experience of the artwork consider:
  - The number of visitors stopping to look
  - The time audience members stay with the work
  - Survey audience members through written means or interview.
- Apply for funding for artists through Science Funding bodies.

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Acknowledgements

- Dr Sadie Jones, Astronomy Public Engagement Leader, Physics and Astronomy, University of Southampton (UoS)
- Professor Diego Altamirano, Senior Lecturer, Physics and Astronomy, UoS
- Professor Mark Sullivan, Head of the Department, Physics and Astronomy, UoS.
- PERu The Public Engagement with Research Unit (PERu) at the UoS.

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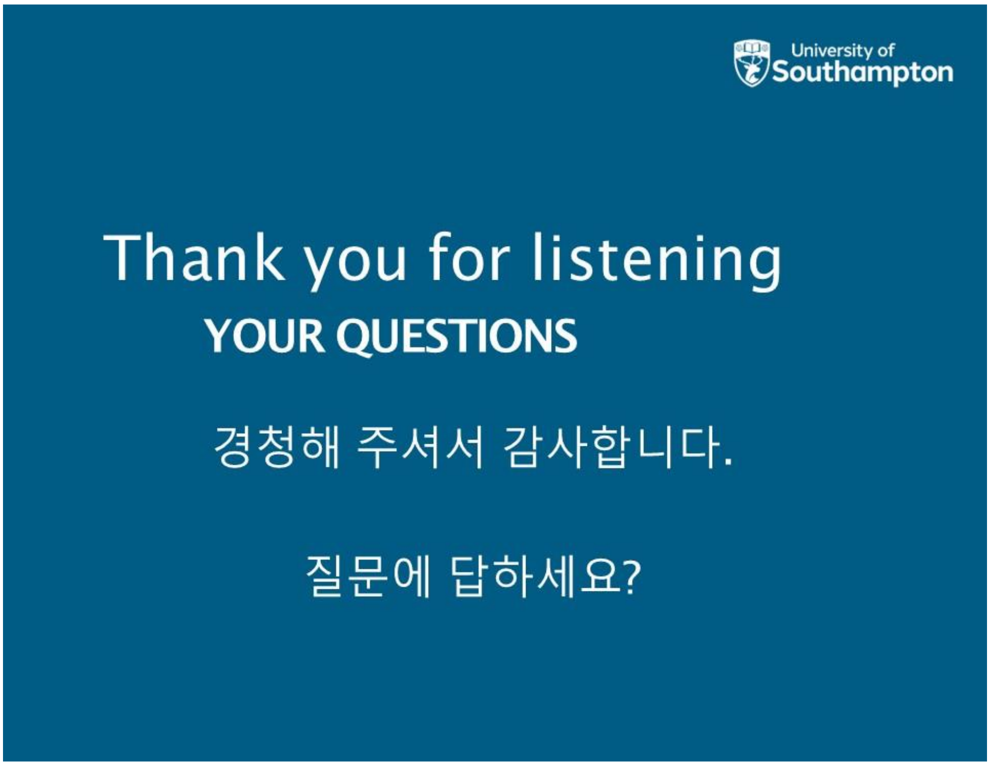
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Thank you for listening
YOUR QUESTIONS
경청해 주셔서 감사합니다.
질문에 답하세요?

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