Research Article

Philippe Gentet, Yves Gentet, Pyeung-Ho Choi, and Seung-Hyun Lee*

Evaluation of the realism of a full-color reflection H2 analog hologram recorded on ultra-fine-grain silver-halide material

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Abstract: This paper presents an evaluation of the realism of a full-color reflection H2 analog hologram recorded on ultra-fine-grain silver-halide material. An H2 hologram is a transplane image that is different from the well-known Denisyuk hologram in which the final image appears fully behind the surface of the glass plate. We explain how to record this type of transplane image on the silver-halide holographic material Ultimate 04. Evaluations are performed using a mixed reality experience questionnaire. The realism of our full-color H2 hologram is successfully demonstrated and shows the potential for its integration into a diorama.

Keywords: full-color H2 hologram, diorama, transplane image, mixed reality

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1 Introduction

As written by Jens Schröter in his book, 3D: History, Theory and Aesthetics of the Transplane Image [1], holography—invented by Dennis Gabor [2] in 1948—is “without a doubt the most complex and the most enigmatic phenomenon in the field of technical transplane images.” But the only reference that most people have about holograms comes from science fiction movies or pepper’s ghost illusion attractions [3]. However, today, many digital holographic technologies are developing rapidly and are now used in various fields such as the military, advertising,

architecture, automotive industry, medical and entertainment, and the creation of a real holographic television is a major research topic and a great challenge of this early 21st century [4, 5]. Thanks to the progress made in recent years with the development of new diode-pumped solid-state (DPSS) lasers and new recording materials (ultra-fine grain silver-halide emulsions and photopolymer materials), analog holography remains popular for museum, artistic or educational applications [6, 7].

The last generation of full-color reflection analog Denisyuk hologram [8] is categorized as ultra-realistic because a spectator can hardly discriminate between the hologram and its real counterpart [9]. Furthermore, it is possible, under certain specific conditions, to copy a Denisyuk hologram to obtain a second-generation hologram, called an H2. This second hologram is no longer only behind the recording glass plate, but in between or even totally floating in front of it. Modern audiences are attracted to these 3D transplane images, which are spectacular, fascinating, and more similar to depictions of holograms in science fiction films.

The technique for producing an H2 from a Denisyuk monochrome hologram is well known [10], but difficult to implement with full-color holograms. In the early 2000s, Dai Nippon Printing (DNP) was the first company to succeed in mass producing full-color H2 holograms, which were marketed under the name TRUE IMAGE™. This was achieved through the use of DuPont panchromatic photopolymer holographic recording material [11]. However, to get bright holograms, DNP has recorded masters (and then copies) with a very limited viewing range [12, 13].

The objective of this research is to record a full-color H2 hologram with a wide field of view and demonstrate that it is realistic enough to be seamlessly integrated into a diorama among other similar real 3D objects. The hypothesis is that one can record such a hologram using the last generation of silver-halide holographic emulsion, Ultimate 04 (U04) [14, 15]. Dioramas are 3D model replicas—full-size or miniature—that often depict historical events or scenes in natural or urban settings. They are commonly enclosed in glass showcases in museums

*Corresponding Author: Seung-Hyun Lee: Ingenium College, Kwangwoon University, Seoul, Korea; Email: shlee@kw.ac.kr

Philippe Gentet: Plasma Bio Display, Kwangwoon University, Seoul, Korea; Email: p.gentet@gmail.com

Yves Gentet: Ultimate Holography, Bordeaux, France

Pyeung-Ho Choi: Plasma Bio Display, Kwangwoon University, Seoul, Korea

[16, 17]. They usually consist of three parts: a background, foreground, and characters. They remain very popular for educational [18], commercial, artistic [19], and entertainment purposes. The authors did not find any examples in the literature in which full-color, ultra-realistic H2 holograms were mixed with real elements; nor any evaluations of a transplane hologram based on perceptions of the general public. In fact, our research is more closely aligned with the modern concept of mixed reality (MR) systems, which supplement real world objects with virtual ones that appear to coexist in the same space [20, 21].

That is why we evaluate the realism of our final H2 hologram from the perspective of the general public with a mixed reality experience questionnaire (MREQ). The MREQ was originally designed by the University of Otago (New Zealand) to be used as a measure of a user's sense of presence and their general experienced perception of mixed reality [22].

2 Materials and methods

2.1 Material to record holograms

Different holograms were recorded on 4" x 5" U04 silver halide holographic glass plates—an isopanchromatic emulsion specially designed for recording full-color analog holograms using all the common visible lasers (442, 457, 473, 488, 514, 532, 633, 640, and 647 nm). The grain size is so fine (4 nm) that any visible wavelength is recorded without diffusion. The minimum typical recommended exposure energy is 200 $\mu\text{J}/\text{cm}^2$ per laser for a full-color RGB hologram.

For our setup, the three red, green, and blue (RGB) wavelengths were as follows: red 633 nm provided by a Thorlabs helium-neon (HeNe) laser, green 532 nm provided by a Cobolt diode-pumped solid-state (DPSS) laser, and blue 473 nm provided by a Cobolt DPSS laser. The three RGB laser beams were combined with an X-cube prism (a glass cube beam splitter with coatings on both diagonals) to produce a white laser beam.

The test object for our experiment was a 7 cm tall, 2.5 cm wide, and 2.5 cm deep colorful toy. In anticipation of its inclusion into a diorama, we recorded our model in front of a black background (Figure 1).

Figure 1: Colorful test object with a black background under RGB light-emitting diode (LED) illumination

2.2 Method to get a full-color H2 reflection analog hologram

The process for creating a transplane reflection H2 hologram consisted of three successive stages. First, we recorded a full-color reflection hologram—an H1—of our test object with the well-known Denisyuk technique, and acquired an image fully behind a glass plate. Subsequently, we sealed the H1 at the exact recording wavelengths with proper optical glue to protect the gelatin from humidity and avoid unwanted color shifting. Finally, the master H1 produced in the first two stages was flipped and used as an object to record a full-color transplane H2 hologram copy.

2.2.1 H1 hologram recording and developing

The H1 hologram was recorded on a U04 glass plate with the single-beam method introduced by Yuri Denisyuk. This technique makes it possible to record an ultra-realistic hologram with a full 180° parallax. To achieve a full-color single-beam reflection Denisyuk hologram, the recording setup uses three lasers simultaneously. For our experiment, the three RGB laser beams with p-polarization were combined with the X-cube prism, and their intensities were adjusted to 20 mW to produce a uniform white laser beam. This white beam then passed into a beam expander/spatial filter to achieve perfectly clean and homogeneous illumination from a distance of 1 m at an angle of 45° to both the object and recording plate (Figure 2). The intensity of each laser at the holographic plate, measured with a power-meter, was 17 $\mu\text{W}/\text{cm}^2$; the exposure time was 12 s.

Figure 2: Full-color single-beam reflection Denisjuk hologram setup

Figure 3: H1 hologram sealed with optical UV glue

Table 1: Ultimate 04 processing steps

Processing Steps	Time (minutes)
Develop in Safe Developer at 22°C	4
Wash under running water	0.5
Bleach in Safe Bleach at 22°C	Until clear
Wash under running water	3
Wash with a drop wetting agent	1
Dry vertically	20

The H1 hologram was then developed in two chemical baths (developer and bleach), as recommended by the U04 manufacturer (Table 1). These chemicals are safe for both holographers and the environment, and easy to use.

2.2.2 Sealing H1 hologram to produce a master

To become a master, the H1 must be reconstructed exactly to the same wavelengths used when recording. To prevent any emulsion thickness variations (swelling or shrinkage) due to changes in humidity or temperature, the hologram

has to be protected by a second glass plate that should be sealed using optical ultraviolet (UV) glue (Figure 3).

2.2.3 H2 hologram recording and developing

When the sealed H1 hologram is examined under a light, the virtual image of the recorded object is seen behind the glass plate. When the H1 is flipped, an inverted floating pseudoscopic real image is observed. This real image floating in front of the glass plate becomes the object for the new H2 hologram (Figure 4).

Usually, when an H2 hologram is recorded, the best visual result is achieved when the final transplane hologram is in between in such a way that part of the object comes forward, and part of the object goes backward. These holographic images appear very sharp, even under light, which is not a good point source. However, to be able to incorporate this transplane hologram into a diorama, our final image has to be completely outside—floating in front of the glass plate. Our H2 hologram was recorded under the same conditions as the H1. The exposure time was also the same

Figure 4: Full-color H2 hologram recording from a master

(12 s) and the H2 was developed according to the same recommended safe process for U04 plates.

2.3 Method to evaluate if the H1 hologram can be considered a master

To be considered a true master that can be replicated into H2 holograms, the H1 hologram has to have good diffraction efficiency (DE) for each wavelength (typically 40% or above), and show no diffusion. To verify the master quality, we visually compare the H1 hologram with the original object, side by side—both illuminated under the white laser beam. They should either have the same brightness, or the H1 should be brighter than the original object. Additionally, the H1 must be totally uniform in color and brightness, and without any visual defects.

If these conditions are not fulfilled, the H1 defects will be amplified in the H2, which will appear darker or more diffuse than the original hologram. On the other hand, when the H1 achieves both high DE and transparency, the H2 is as good as the original or even brighter since H1 keeps the polarization of the laser.

2.4 Method to calculate the H2 horizontal field of view

The horizontal field of view of an H2 hologram directly depends on the width of the H1 hologram and the distance between the H1 and H2. As such, to obtain the maximum

horizontal parallax, the holographic plate used to record the master must be as wide as possible.

If w is the width of the H1 hologram and d the distance between the two holograms when recording, the value of the H2 horizontal parallax, θ , is given by the expression:

$$\theta = 2 \arctan\left(\frac{w}{2d}\right) \quad (1)$$

2.5 Method to evaluate the realism of the H2 hologram

2.5.1 Hypothesis

We posed three hypotheses to evaluate the realism of our full-color H2 hologram and the possibility of its integration into a diorama among similar real objects:

- Hypothesis 1: a full-color H2 hologram looks like a real 3D object.
- Hypothesis 2: a full-color H2 hologram looks like its real 3D counterpart.
- Hypothesis 3: a full-color H2 hologram can be integrated into a diorama among other similar real 3D objects.

2.5.2 Participants

Fifty-four people of different nationalities consisting of sixteen women and thirty-eight men, between the ages of twenty-one and sixty-five participated in our survey. All participants had normal or corrected-to-normal vision and

provided us with informed verbal consent. All Participants were volunteers and no compensation was offered.

2.5.3 Experimental Design

Two experimental setups were used to verify the hypotheses. In the first setup, the H2 hologram was displayed alone, without a frame, and illuminated with an RGB LED lamp at a proper distance (50 cm) to avoid any blur. In the second setup, another copy of our H2 hologram was integrated into the background of a diorama, and the whole setup was illuminated with the same RGB LED lamp. A polarizer was placed in front of the diorama to reduce unwanted reflections on the real objects.

All observations were performed under dimmed ambient light (as in a museum) of 150 lumen/m², without any direct lighting other than our RGB LED lamp. All participants were warned prior to observation that they would see full-color holograms. No further technical explanations were given. Each participant successively observed the H2 hologram, the real counterpart (illuminated with the same RGB LED lamp), and the enhanced diorama with the H2 hologram at a distance of about 50 cm. Participants were free to step back, move right or left, approach, and touch objects. After observation, each participant filled out an MREQ specifically adapted for the study of holograms.

2.5.4 Survey

Our survey consisted of the following 6 questions (in each question, the word hologram refers to the H2 image):

1. Watching the hologram was just as natural as watching the real world.
2. The hologram seemed real to me.
3. The hologram and I were in the same environment (I felt I could have touched the hologram).
4. The hologram looked visually the same as its real counterpart.
5. In the diorama, I could not distinguish between a real object and the hologram.
6. Watching the diorama was just as natural as watching the real world.

All questions were answered according to a 7-point Likert-type scale [23]. Answers ranged from 1, meaning “strongly disagree,” to 7, meaning “strongly agree;” no other qualifying information was given (e.g., no middle anchor text). The response to each question can be analyzed separately, and related questions can be summed to create

Table 2: Cronbach’s alpha rules

Cronbach’s alpha	Internal consistency
$0.9 \leq \alpha$	Excellent
$0.8 \leq \alpha \leq 0.9$	Good
$0.7 \leq \alpha \leq 0.8$	Acceptable
$0.6 \leq \alpha \leq 0.7$	Questionable
$0.5 \leq \alpha \leq 0.6$	Poor
$\alpha < 0.5$	Unacceptable

a score for a group of statements (Likert-type scales are often referred to as summative scales).

2.5.5 Data analysis

First, Cronbach’s alpha (α) [24] was calculated to analyze the reliability or internal consistency (how closely related a set of items are as a group) of our questionnaire. Cronbach’s alpha is computed by correlating the score for each scale item with the total score for each observation (individual survey respondents) and comparing that result to the variance of all individual item scores. The resulting α coefficient of reliability ranges from 0 (items are entirely independent of one another) to 1 (all of the items have high covariance).

The rules commonly accepted [25] by many methodologists for describing internal consistency using Cronbach’s alpha for Likert-type scale questions are shown in Table 2. A high alpha means that the items in the test are highly correlated.

3 Results

3.1 H1 hologram

An H1 hologram of the test object was recorded on a 4” x 5” U04 glass plate according to the Denisyuk method and developed in two chemical baths. After processing, a blur-free, ultra-realistic, colorful, transparent 1:1 scale image, with high DE (greater than 40%) for each wavelength was obtained.

When illuminated at the proper distance with an RGB LED lamp, a sharp holographic reconstruction of the object appeared completely behind the glass plate surface with a 180° parallax, both horizontally and vertically (Figure 5). The H1 hologram was then sealed to prevent emulsion thickness variations and color changes.

Figure 5: Sealed full-color reflection H1 hologram under RGB LED illumination

3.2 Evaluation of the H1 hologram

When we visually compared the sealed H1 hologram side by side with the original real object, both illuminated by the white laser beam, they presented the same brightness (Figure 6).

Furthermore, the H1 was totally uniform in color and brightness, and without any visual defects. The H1 could therefore be considered a true master and used to record the H2.

Figure 6: Original real object (left) and the H1 hologram (right) under white laser beam illumination

3.3 H2 hologram

According to the method, the H1 was flipped and became the object to record the new H2 hologram. A colorful, transparent transplane image with a wide field of view, high DE for each wavelength, and without any noise was obtained when the H2 hologram was illuminated with an RGB LED at the proper distance (Figure 7). The character floated completely in front of the glass plate.

As the depth of our object is 2.5 cm and the width of our holographic plate is 10 cm, the horizontal field of view of our final image was approximately 125° , according to formula (1).

Figure 7: Full-color reflection H2 hologram under RGB LED illumination

3.4 Diorama

The H2 hologram was integrated into the background of a diorama. The dimensions of the diorama were as follows: 15 cm wide, 15 cm high and 10 cm deep. In addition to the H2 hologram, it was composed of several objects with similar texture and color to that of our model (Figure 8). With the objects and edges of the diorama reducing the field of view to 120° , the H2 hologram did not present any deformation when the viewer moved horizontally.

Figure 8: Diorama with real objects and the H2 hologram

Figure 9: Distribution of responses of the 54 participants.

3.5 Survey

Cronbach’s alpha showed a very high internal consistency of the questionnaire ($\alpha = 0.990$). Figure 9 shows the bar chart distribution of participant responses.

For all of our 7-point Likert-type scale survey questions, the mode (most frequent) response was 7, “strongly agree.” The median response was also 7 for all questions except 4 (The hologram looked visually the same as its real counterpart), where it was 6 (Table 3).

Table 3: Mode and median for the questions 1 to 7

Question	1	2	3	4	5	6
Mode	7	7	7	7	7	7
Median	7	7	7	6	7	7

4 Discussion

Our H1 and H2 holograms were recorded on silver halide emulsion glass plates. The main advantage of silver halide emulsions (like U04) compared with photopolymers is a

much higher sensitivity (300–500 times). The resulting shortened exposure time is often preferred for recording holograms with high DE in analog holography to avoid vibration and movement problems. The substrate material is also important to the final hologram quality, and the best choice is glass because it is mechanically stable and optically inactive. The main advantage of photopolymers is their dry processing. Comparatively, U04 requires wet processing, but it remains fast and simple, and uses non-toxic products.

Our H1 was totally uniform in color and brightness, and without any visual defects. It had high DE for each wavelength, and showed no diffusion. The grain size of U04 is so fine (4 nm) that any visible wavelengths—including blue—are recorded without diffusion. If this is not fully exploited, the H1 defects will be amplified in the H2, appearing darker or more diffused than in the original hologram. Sealing the H1 is one method for ensuring a bright H2. Indeed, if the H1 hologram is not exactly reconstructed when copying—at the same wavelengths as it was recording—the brightness of the H2 suffers.

As our H1 had sufficient qualities to be master, a colorful and transparent H2 hologram with high DE was obtained and then evaluated with our questionnaire. For questions 1, 2, and 3, the mode and median were each 7. These results verified the first hypothesis (a full-color H2 hologram looks like a real 3D object). The majority of survey participants perceived the H2 hologram as a real 3D object. For the second hypothesis (a full-color H2 hologram looks like its real 3D counterpart), the majority of participants perceived the H2 hologram as similar, but not identical to its real counterpart. As such, the corresponding question 4 had a median of 6. The third hypothesis (a full-color H2 hologram can be integrated into a diorama among other similar real 3D objects) was also verified. The majority of participants were unable to discern real from virtual. The mode and the median for the corresponding questions (5 and 6) were 7. This survey shows that the realism of our full-color reflection transplane image can be categorized as ultra-realistic because most of the spectators could hardly discriminate between our hologram and a real object. This illustrates the possibility of integrating H2 images into dioramas among other real 3D objects.

5 Conclusion

This study—thanks to a full-color reflection H2 analog hologram recorded with U04 silver halide holographic emulsion plates—indicates that it is possible to record

ultra-realistic transplane holograms with sufficient quality to be integrated into real 3D worlds. This holographic technique can be used for museum or artistic applications. The authors are planning several improvements in the future. By manipulating the lighting, it might be possible to make true 3D holographic objects appear or disappear in decors and interact with the public. This first result shows the feasibility of integrating ultra-realistic, full-color H2 analog holograms into mixed reality experiences for a modern audience.

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