Computer-generated holograms for 3D display

Invited Paper

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We have been studying various types of computer-generated holograms for three-dimensional (3D) displays both for a real-time holographic video display and a hard copy, or a printed hologram. For the hard copy output, we have developed a direct fringe printer, which is achieved to print over 100 gigapixels computer-generated hologram with 0.44-μm pitch. In this paper, we introduce our recent progresses on the rainbow hologram, the cylindrical holograms, and the disk hologram for 3D display.

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1. Introduction

The progress of the personal computer (PC) performance makes it possible to calculate the computer-generated holograms (CGH) of three-dimensional (3D) objects that have more than ten gigapixels[1−4]. We have been studying on CGH for 3D display and early works are published as a book chapter[5], which includes the rainbow hologram, the rainbow holographic stereogram, and the hybrid hologram—an optically transferred hologram from a CGH master. We have been working both calculation methods and the output device of CGH. For the CGH output, we have developed the holographic fringe printer consisting of a laser, a spatial light modulator (SLM), and X-Y translation stage with stepper motors. In this letter, we introduce our recent progress on CGHs. It includes the computer-generated rainbow hologram of 249600×174080 pixels with the pixel pitch of 0.44 μm. This pixel pitch is good enough for the direct observation of 3D images. Also, we have proposed some display forms such as the full-parallax cylindrical type, the full-color cylindrical rainbow type, and the disk type. With the fringe printer, we could get the good reconstructed images from these forms.

2. Fringe printer

Figure 1 shows a schematic of the fringe printer[1,6]. Light from the laser is collimated and incident on a liquid crystal on silicon (LCoS). The holographic fringe pattern is displayed on the LCoS and the demagnified image is projected on a holographic plate. Convex lenses L3 and L4 form the telecentric imaging system whose demagnification factor is the ratio of the focal lengths of the lenses. The shutter is opened while the exposure and the holographic plate are then translated by the X-Y translation stage for the next exposure to shape the larger printing area by tiling elemental holograms. The stage can travel 200×200 mm^2 with the resolution of 4 μm. The laser is a Nd:YAG + LBO diode-pumped solid-state (DPSS) laser whose wavelength is 473 nm and power is 5 mW.

The LCoS panel is originally a component of the high-definition television (HDTV) projector (Sony VPL-VW50). Its resolution is 1920×1080 pixels with 7-μm pitch. The holographic fringe pattern on the LCoS panel is demagnified by the convex lenses L3 and L4 (the lens L4 of the present system is a Fresnel lens), forming the telecentric system. The demagnification factor is the ratio of focal lengths of the lenses, and the focal lengths of L3 and L4 are 200 and 12.5 mm, respectively. Therefore, the demagnification factor is 16, and the pixel pitch of the printed hologram is 0.44 μm. The pitch corresponds to the diffraction angle of 46° for red light ($\lambda = 633$ nm) and 32.5° for blue light ($\lambda = 473$ nm). As a recording material for the fringe printer, we used VRP-M holographic film manufactured by Slavich. The current printing time is 18 min per one gigapixels.

3. Computer-generated rainbow hologram

For the full color reproduction, we have employed the computer-generated rainbow hologram (CGRH)[7]. Table 1 shows the parameters of the CGRH. Figure 2 shows the perspective computer-generated image of the recorded object represented by about 510000 points. Since the pixel pitch of the printed hologram becomes fine, the viewing zone also becomes wide. Therefore, if we use a single set of self-illuminated points, the absence

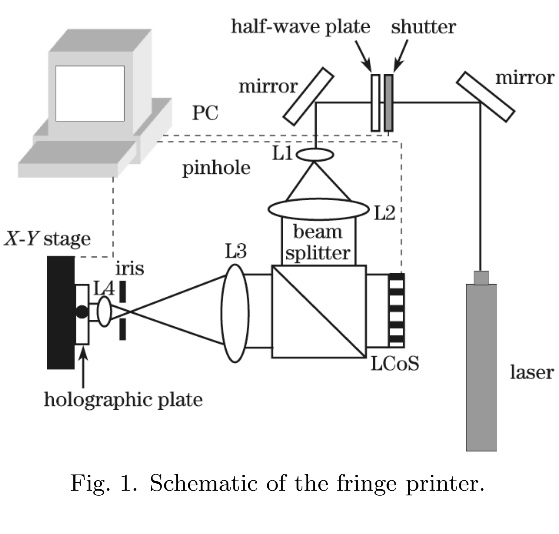

Fig. 1. Schematic of the fringe printer.

of the hidden surface's data and the overlap of the object points appear when the viewer moves. To solve these problems, we employed the image type hidden surface removal method[8].

Figure 3 shows the reconstructed images of CGRH. The reconstructed images exhibit good color reproduction and high contrast. Also the absence of the hidden surface and the overlap of the object points are not observed even if the viewpoint changes.

4. Computer-generated cylindrical hologram

Since a general flat type hologram has a limited viewable area, we usually cannot see the other side of a reconstructed object. Therefore, we employed the cylindrical hologram to achieve the 360° viewable CGH. A cylindrical hologram was proposed by Jeong[9]. This hologram can be seen from all sides. Since the optical system is simple, it is easy to make the cylindrical hologram. Figure 4 shows the optical setup for recording the optical cylindrical hologram. A film is set in the cylindrical shape, and an object is placed at the center of the film. To record the hologram, an expanded laser beam illuminates the object and the film. For the reconstruction, the same laser beam is used to illuminate the hologram. Since the shape of the hologram is a cylinder, the reconstructed image has a 360° viewable area.

Table 1. Parameters of CGRH

Parameter	Value
Resolution (pixel)	249600 × 174080
Size (mm^2)	110 × 76.6
Object Size (mm^3)	105 × 74 × 60
Pitch (μm)	0.44
Wavelengths (nm)	473, 532, 633
Number of Object Points	510000

Fig. 2. Computer-generated image of the recorded object.

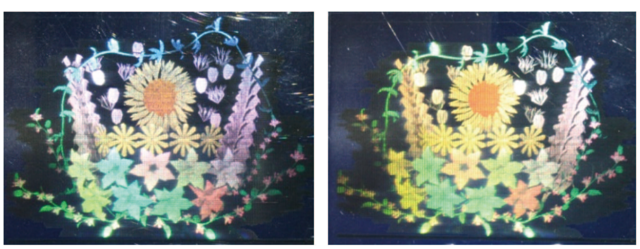

Fig. 3. Reconstructed images of CGRH from different viewpoints.

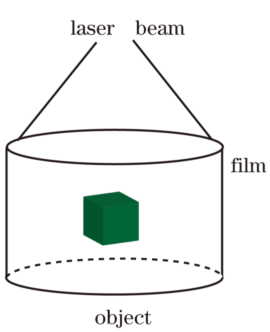

Fig. 4. Optical arrangement for making a cylindrical hologram.

Since the surface area of the cylindrical hologram is large, the calculation amount is very huge. Therefore, we employ graphics processing unit (GPU) for the fast calculation[10]. Table 2 shows the parameters of the computer-generated cylindrical hologram (CGCH). Figure 5 shows the perspective images of the object from several viewpoints. The average number of the object points is approximately 27000. It took 32 hours to record the whole hologram of 98 gigapixels. The total calculation time is about 95 hours with one PC (GPU: 8800GTX). Figure 6 shows the reconstructed images of the CGCH from several viewpoints. The reconstructed images are crisp and exhibit good contrast. Comparisons with Fig. 5 show that the reconstructed images are almost the same as the perspective images.

5. Computer-generated cylindrical rainbow hologram

We also investigate the color CGCH with the rainbow hologram[3,7]. To fit the cylindrical hologram, the optical model is changed, as shown in Fig. 7. Since the shape

Table 2. Parameters of CGCH

Parameter	Value
Resolution (pixel)	912000 × 108000
Size (mm^2)	556 × 65.9
Radius (mm)	88.5
Object Size (mm^3)	17 × 17 × 17
Pitch (μm)	0.61
Wavelength (nm)	633
Number of Object Points	27000 (Average)

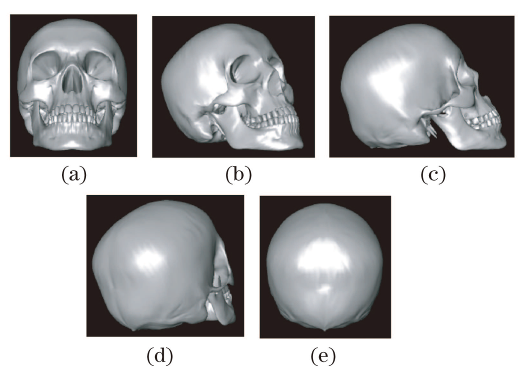

Fig. 5. Perspective images of the object data from several viewpoints.

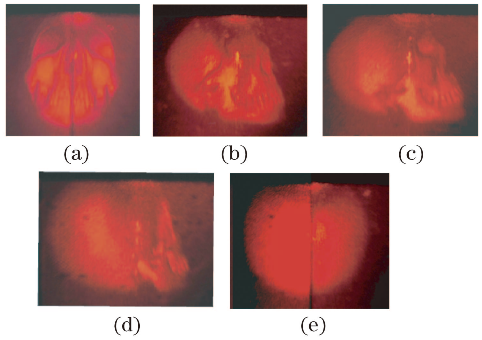

Fig. 6. Reconstructed images of cylindrical hologram from several viewpoints.

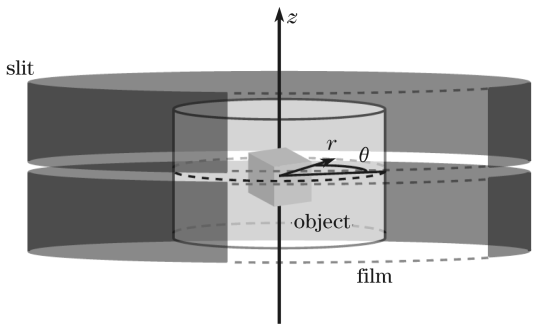

Fig. 7. Rearranged slit for CGCRH.

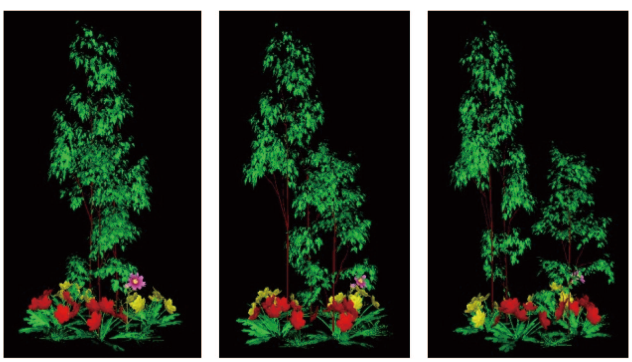

Fig. 8. Perspective images of the object data from several viewpoints.

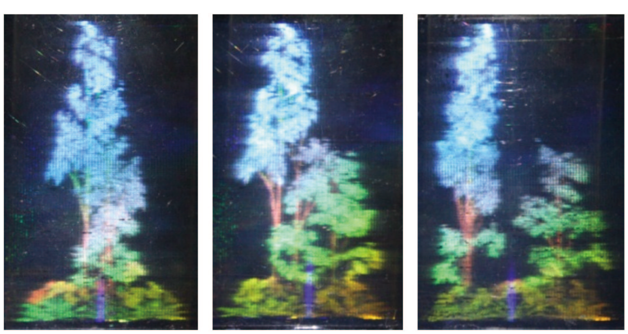

Fig. 9. Reconstructed images of the cylindrical rainbow hologram from several viewpoints.

of the computer-generated cylindrical rainbow hologram (CGCRH) is cylindrical, the straight slit is converted to a cylindrical slit.

Table 3 shows the parameters of the CGCRH. To enlarge the vertical object size, the CGCRH is illuminated by the collimated light with the corn mirror[4]. Figures 8 and 9 show the perspective images of the object and reconstructed images from several viewpoints. The total recording time is about 75 hours for 245 gigapixels. The full color reconstructed images are crisp and exhibit good contrast.

Table 3. Parameters of CGCRH

Parameter	Value
Resolution (pixel)	1228800 × 199680
Size (mm^2)	494 × 78.7
Radius (mm)	78.7
Object Size (mm^3)	45 × 78.4 × 45
Pitch (μm)	0.44
Wavelengths (nm)	473, 542, 633
Incident Angle of Reference Light (rad)	0.45
Number of Object Points	27000 (Average)

6. Computer-generated disk hologram

As the other type of the 360° viewable hologram, we have been investigating the computer-generated disk hologram (CGDH)[3]. Since the CGCH has the cylindrical shape, it is difficult to build the CGCH and the calculation amount is too huge. In contrast, a disk type hologram[11] is also well known as the 360° viewable hologram. Since the disk hologram is the reflective type flat hologram, the setup of reconstruction is very easy and it can be reconstructed with the white illumination light.

Table 4 shows the parameters of the master hologram of CGDH. Figure 10 shows the optical setup to record a transfer hologram from the reconstructed image of the master hologram[3]. The master hologram is also a disk hologram. However, it is a laser

Table 4. Parameters of CGDH

Parameter	Value
Resolution (pixel)	167936 × 167936
Size (mm^2)	102 × 102
Object Size (mm^3)	8 × 8 × 8
Pitch (μm)	0.61
Wavelength (nm)	633
Number of Object Points	600

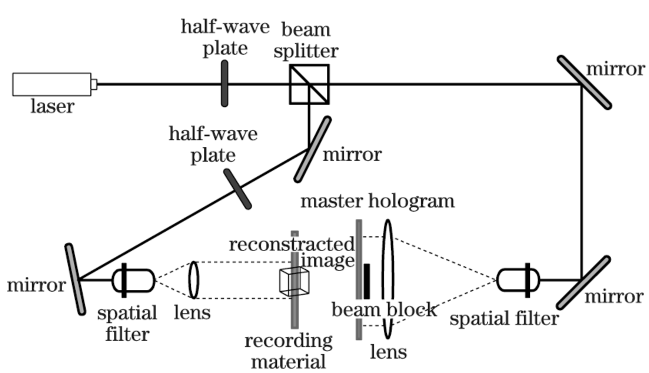

Fig. 10. Optical setup for recording the transfer hologram.

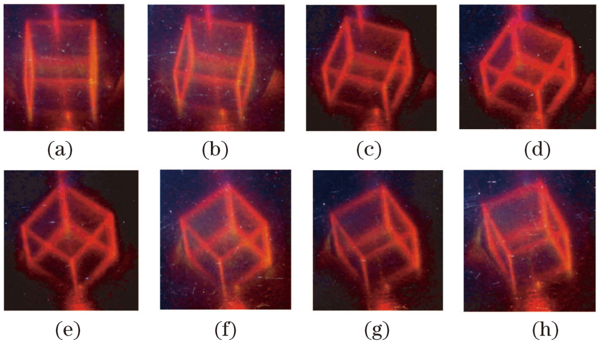

Fig. 11. Reconstructed images of the CGDH from several viewpoints.

transmission hologram. Therefore, we make the transfer hologram as the reflection hologram for the simple illumination and white-light reconstruction. The beam block is used to eliminate the zero order diffracted light from the master hologram. Figure 11 shows the reconstructed images of the CGDH from several viewpoints. The reconstructed images are crisp and exhibit good contrast. As the reconstructed images change with different viewpoints, we have also achieved CGDH as the 360° viewable CGH.

7. Conclusion

We have introduced our recent results of CGHs for 3D display including the flat rainbow hologram, the cylindrical hologram, the cylindrical rainbow hologram, and the disk hologram. With the improved fringe printer, it is now possible to print over 100 gigapixels holograms with 0.44-μm pitch. Since such huge pixel number hologram can be printed, the calculation and printing speed become very significant. The details of optical models, calculation methods, and experimental results are described in original papers.

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References

1. T. Yamaguchi, M. Matuoka, T. Fujii, and H. Yoshikawa, in *Proceedings of Eighth International Symposium on Display Holography* (2009).
2. T. Yamaguchi, T. Fujii, and H. Yoshikawa, Appl. Opt. **47,** D63 (2008).
3. T. Yamaguchi, M. Tsumuta, T. Fujii, and H. Yoshikawa, Proc. SPIE **7233,** 723314 (2009).
4. T. Yamaguchi, T. Fujii, and H. Yoshikawa, Opt. Eng. **48,** 055801 (2009).
5. H. Yoshikawa, "Computer-generated holograms for white light reconstruction" in T.-C. poon, (ed.) *Digital Holography and Three-Dimensional Display: Principles and Applications* (Springer, New York, 2006).
6. H. Yoshikawa and K. Mitsui, in *Proceedings of Seventh International Symposium on Display Holography* 102 (2006).
7. H. Yoshikawa and H. Taniguchi, Opt. Rev. **6,** 118 (1999).
8. T. Fujii and H. Yoshikawa, in *Proceedings of OSA Digital Holography and Three-Dimensional Imaging* DWB3 (2007).
9. T. H. Jeong, J. Opt. Soc. Am. **57,** 1396 (1967).
10. S. Matsuda, T. Fujii, T. Yamaguchi, and H. Yoshikawa, Proc. SPIE **7233,** 72330I (2009).
11. J. Kim, J. Hill, J. Honack, W. Roth, R. Roberts, E. Villasenor, O. Gonzales, and E. Baker, Proc. SPIE **2333,** 418 (1994).