Frontier in Optics + Laser Science 2022, Rochester, USA, FM5E.2 (2022.10.17, Invitaed talk).

Challenges to Tera-pixel-scale Full-parallax Computer Holography for 3D Imaging

Kyoji Matsushima* and Hirohito Nishi
Department of Electrical, Electronic and Information Engineering, Kansai University, 3-3-35 Yamate-cho, Suita, Osaka 564-8680, Japan
**Corresponding author e-mail: matsu@kansai-u.ac.jp*

Abstract: Computer holography requires a trillion pixels and a full-parallax view to reconstruct quality three-dimensional images comparable to those reconstructed in traditional optical holography. Large-scale full-parallax computer-generated holograms are presented to introduce state-of-the-art computer holography.

1. Introduction

Clear three-dimensional (3D) imaging in the field of holography was realized in the early 1960s by the pioneers Yuri Denisyuk, Emmett Leith, and Juris Upatnieks. Leith and Upatnieks displayed their first laser holograms in 1964 at the annual meeting of the OSA. This can be considered the birth of 3D holographic imaging in practice because previous 3D holographic images were not clear owing to a lack of coherent light sources. Since then, although many techniques and materials have been invented and developed to record and reconstruct excellent 3D holographic images, the technology has remained essentially the same. The 3D image is recorded on light-sensitive material as a continuous fringe pattern, and the physical subject is needed to produce the 3D image; the image of virtual objects cannot be reconstructed unlike computer graphics. Traditional holography is not considered as a modern digital technology because the holograms cannot be stored and transmitted with digital media.

The nature of a hologram is the fringe pattern generated by interference with a reference wave. The origin of the concept of computer-generated holograms (CGHs), where the fringe pattern is calculated by computers, goes back to the days immediately after the realization of 3D imaging in optical holography. However, CGHs comparable to optical holograms were not realized until recently. This is entirely due to the extremely large space-bandwidth product (SBP) required for quality holograms. The SBP of typical optical holograms is estimated to exceed 1 trillion; i.e., the fringes are considered to be a tera-pixel-scale image.

Over the past 15 years, we have developed computer holography to create quality CGHs for 3D imaging [1]. The maximum SBP has reached approximately 0.2 trillion as of August 2022 and is predicted to exceed 0.5 trillion within a year. These large-scale CGHs reconstruct not only monochromatic images but also full-color images. The impressive full-parallax 3D images give an amazing sensation of depth to the viewer, which has not been realized by other technologies. Some of the latest CGHs are introduced and demonstrated in this paper.

2. Necessary SBP and parallax

The viewing angle of a CGH (i.e., the angular range that the viewer can move the viewpoint) is mainly determined by the pixel pitches Δx and Δy of the fringe image (see Sec. 8.3 in [1]). As an example, when $\Delta x = \Delta y = 0.6$ μm, the viewing angle of the CGH is 48° in blue color (488 nm). As a result, when we create a CGH with the dimensions of a 40-inch high-definition television (88.4 cm × 49.8 cm), the number of pixels is approximately 1.22 T pix.

It is difficult to generate a tera-scale fringe image using computers within a realistic computational time. The easiest way to reduce the problem is to restrict the parallax to the horizontal direction. The computational cost of a horizontal-parallax-only CGH (HPO-CGH) is the square root of that of the full-parallax CGH. However, when we view the 3D image reconstructed by an HPO-CGH, there is inevitably conflict between the horizontal and vertical accommodation of the eyes. The conflict loses the advantage of holographic 3D displays, i.e., the ability to reconstruct a deep 3D scene naturally.

3. Giga-scale to quasi-tera-scale CGHs

We refer to full-parallax CGHs of more than 1 billion pixels as full-parallax high-definition CGHs (FPHD-CGHs). The first FPHD-CGH was The Venus created in 2009 [2]. The fringe of The Venus comprised 4.2 G pix and was printed adopting laser lithography (see Sec. 15.3 in [1]). The object field was calculated using the polygon-based method [3]; only mutual occlusion between separate objects was processed in this CGH using the silhouette method [4]. To realize FPHD-CGHs, although we have developed several numerical techniques in the field of wave optics [5–7], the computation time of The Venus was 48 h in 2009. Nowadays the same CGH can be calculated in 20 min and complicated self-occlusion can be properly processed using the switch-back technique [8]. CG-modeled 3D objects are reconstructed with not only diffusive surfaces but also specular surfaces [9,10]. Real objects can be incorporated into a 3D scene of virtual objects [11,12]. We can reconstruct FPHD-CGHs in full-color with the two methods [13,14]. Recently, we have developed a new technique to create flipbooks of FPHD-CGHs [15].

Figure 1 shows one of the latest monochrome FPHD-CGHs, which has dimensions of 34 cm × 17 cm. The number of pixels is approximately 0.18 T; i.e., the CGH is of quasi-tera-pixel scale. Additionally, the latest full-color FPHD-CGH is shown in Fig. 2. This is a full-color version of the monochrome CGH named Brothers, which was exhibited at the museum of the Massachusetts Institute of Technology in 2012 [16]. The fringe image comprises 0.1 T pix and RGB color filters are used for full-color reconstruction [11].

4. Conclusion

We demonstrated the latest FPHD-CGHs in monochrome and full color on a quasi-tera-pixel scale.

This work was partially supported by Japan Society for the Promotion of Science (JSPS) KAKENHI 22H03712.

5. References

[1] K. Matsushima, *Introduction to Computer Holography*, (Springer, 2020).
[2] K. Matsushima, S. Nakahara, “Extremely high-definition full-parallax computer-generated hologram created by the polygon-based method,” Appl. Opt. **48**, H54-H63 (2009).
[3] K. Matsushima: “Computer-generated holograms for three-dimensional surface objects with shade and texture,” Appl. Opt. **44**, 4607-4614 (2005).
[4] A. Kondoh, K Matsushima, “Hidden surface removal in full-parallax CGHs by silhouette approximation,” Syst. Comput. Jpn. **38**, 53–61 (2007)
[5] K. Matsushima, H. Schimmel, F. Wyrowski, “Fast calculation method for optical diffraction on tilted planes by use of the angular spectrum of plane waves,” J. Opt. Soc. Am. **A20**, 1755-1762(2003).
[6] K. Matsushima, T. Shimobaba, “Band-limited angular spectrum method for numerical simulation of free-space propagation in far and near fields,” Opt. Express **17**, 19662-19673 (2009).
[7] K. Matsushima, “Shifted angular spectrum method for off-axis numerical propagation,” Opt. Express **18**, 18453-18463 (2010).
[8] K. Matsushima, M. Nakamura, S. Nakahara, “Silhouette method for hidden surface removal in computer holography and its acceleration using the switch-back technique,” Opt. Express **22**, 24450-24465(2014).
[9] H. Nishi, K. Matsushima, S. Nakahara, “Rendering of specular surfaces in polygon-based computer-generated holograms,” Appl. Opt. **50**, H245-H252 (2011).
[10] H. Nishi, K. Matsushima, “Rendering of specular curved objects in polygon-based computer holography,” Appl. Opt. **56**, F37-F44 (2017).
[11] K. Matsushima, Y. Arima, S. Nakahara, “Digitized holography: modern holography for 3D imaging of virtual and real objects,” Appl. Opt. **50**, H278-H284 (2011).
[12] K. Matsushima, N. Sonobe, “Full-color digitized holography for large-scale holographic 3D imaging of physical and nonphysical objects,” Appl. Opt. **57**, A150-A156 (2018),
[13] Y. Tsuchiyama, K. Matsushima, “Full-color large-scaled computer-generated holograms using RGB color filters,” Opt. Express **25**, 2016-2030 (2017).
[14] O. Kunieda and K. Matsushima, “High-quality full-parallax full-color three-dimensional image reconstructed by stacking large-scale computer-generated volume holograms,” Appl. Opt. **58**, G104-G111(2019).
[15] Press release, https://www.kddi-research.jp/english/newsrelease/2022/050901.html
[16] K. Matsushima, S. Nakahara, “Stepping closer to the perfect 3D digital image,” SPIE Newsroom, (7 Nov. 2012).

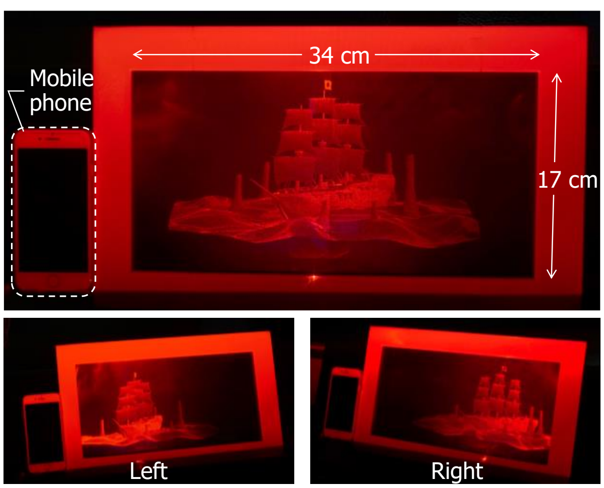

Fig.1 Optical reconstruction of the monochrome FPHD-CGH named Sailing Warship III. The fringe image comprises 425,000 × 425,000 pixels with a pixel pitch of 0.8 μm × 0.4 μm. The illumination light source is a red laser.

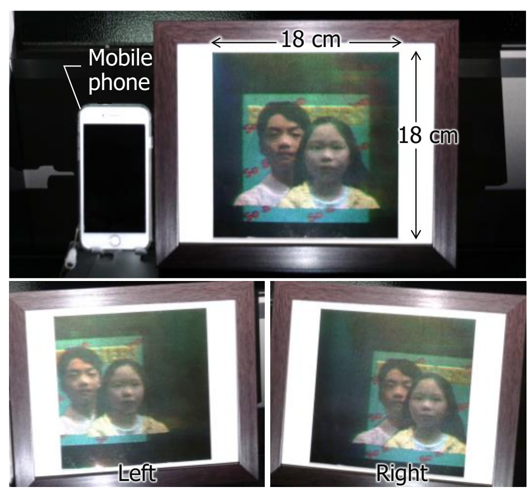

Fig.2 Optical reconstruction of the full-color FPHD-CGH named Color Brothers. The fringe image comprises 225,000 × 450,000 pixels with a pixel pitch of 0.8 μm × 0.4 μm. The illumination light source is an RGB laser.