Compact Binocular Holographic Head-Mounted Display Using Viewing Zone Expansion Method with Multiple Light Sources

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ABSTRACT

Holographic head mounted displays (HMDs) for augmented reality (AR) are being researched for use as work support because they can display images at a free depth. It is necessary to miniaturize the size of such devices for practical use. This paper proposes a compact binocular HMD for AR.

1. INTRODUCTION

Nowadays, head-mounted displays (HMDs) are increasingly being studied, and new technology such as augmented reality (AR) is also becoming popular. HMDs for AR are expected to be used in many applications such as those for work support, in the medical field, and for sports spectating. Some of the HMDs for AR currently being produced include Google Glass by Google and MOVERIO by Epson. However, these HMDs can display images at only one depth, which makes it difficult for viewers to focus their eyes on both real objects and images at the same time. In contrast, holography[1] is considered an ideal 3D display technology because it can display images at a free depth. Holographic HMDs have thus been increasingly researched, and compact holographic HMDs have recently been developed[2, 3].

However, holography has a problem in that the viewing zone is narrow. Also, the pupil distance (PD) is different for each person. Due to these problems, it is difficult to develop binocular holographic HMDs. While several have been researched[4], they are huge and heavy, and they mechanically adjust the position of the viewing zone according to the PD of the user.

One viewing zone is determined by one light source, and as a light source moves, the viewing zone given by the light source also moves. Therefore, it should be possible to provide a wide viewing zone by utilizing multiple light sources. In this paper, we propose a viewing zone expansion method with multiple light sources and present the compact binocular holographic HMD we developed using that method.

2. HOLOGRAPHY

Holography is a stereoscopic display technique that uses refraction and interference of light. Considered an ideal 3D display technology, it meets all the physiological factors for stereoscopic viewing, namely, congestion, focus adjustment, and binocular parallax. It has processes of recording and reconstruction.

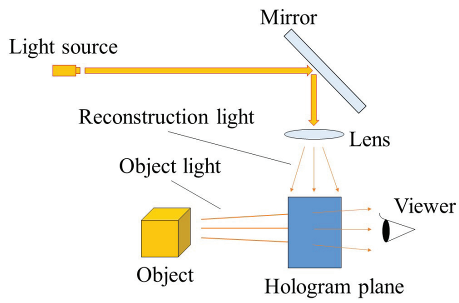


Fig. 1 Reconstruction of holography

In the recording process of holography, light from a light source is split into two by a beam splitter. One is object light, which is defined as optical wave propagation from an object to a hologram plane, and the other is reference light, which is defined as optical wave propagation directly to the hologram plane. An interference pattern called a hologram is recorded by the interference of object light and reference light. The reconstruction process of holography is shown in Fig. 1. 3D images are reconstructed by irradiating the hologram with reproduction light. The reconstruction light used in the reconstruction process is defined as light that has properties equal to the reference light in the recording process.

2.1 Electro-holography

Electro-holography is a technology that displays holographs by means of an electronic device such as a liquid crystal display (LCD). The Fourier transform optical system (FTOS) is one example of electro-holography[5], its outline is shown in Fig. 2. The visual field angle θ and the size of the FTOS viewing zone are expressed by

$$\theta = 2\tan^{-1}\left(\frac{S}{2f}\right) \quad (1)$$

$$w = \frac{\lambda f}{p}, \quad (2)$$

where S is the size of the LCD, f is the focal length of the lens, λ is the wavelength, and p is the pixel pitch of the LCD.

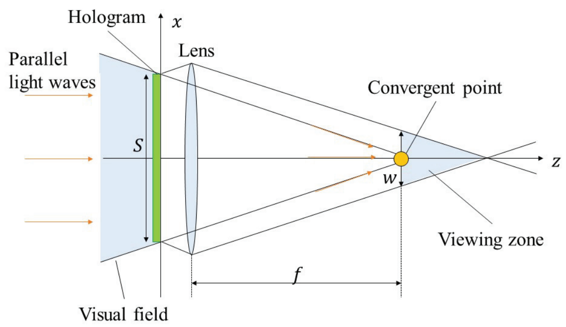


Fig. 2 Outline of FTOS

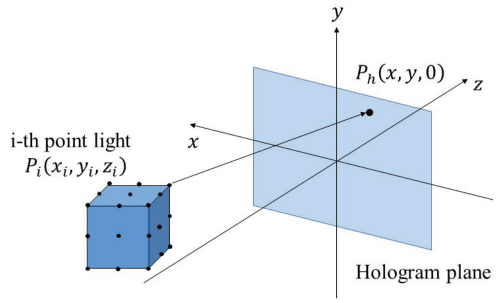


Fig. 3 Wave propagation using point-based method

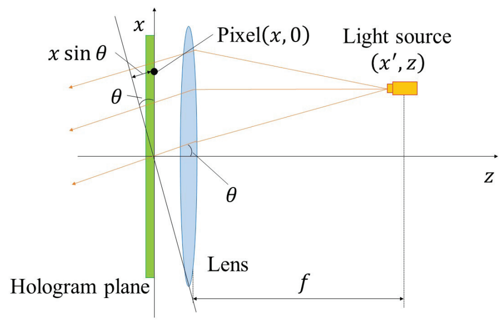


Fig. 4 Calculation of reference light

2.2 Computer-generated hologram

A computer-generated hologram (CGH) is a hologram that is calculated by simulating the process of recording the hologram. Reconstructed images can be observed by displaying CGHs on a reproduction apparatus such as an LCD and irradiating the reconstructed light. In this study, we calculate CGHs by the point-based method[6], which defines an object as a collection of light sources (Fig. 3). We assume that an object is composed of N point-light sources. The propagation distance r_i from an i-th point-light source $P_i\left(x_i, y_i, z_i\right)$ to a point $P_h\left(x, y, 0\right)$ is expressed by

$$r_i = \sqrt{\left(x_i - x\right)^2 + \left(y_i - y\right)^2 + \left(z_i - z\right)^2}, \tag{3}$$

The complex amplitude $O_i\left(x, y\right)$ of the point P_i is expressed by

$$O_i\left(x, y\right) = \frac{a_i}{r_i}\exp(-jkr_i) \tag{4}$$

$$k = \frac{2\pi}{\lambda}, \tag{5}$$

where a_i is the amplitude of point P_i and k is the wavenumber. Since the object is composed of N point-light sources, the complex amplitude $O\left(x, y\right)$ of the object light on the hologram plane is expressed by

$$O\left(x, y\right) = \sum_{i=1}^{N} O_i(x, y). \tag{6}$$

In this paper, we use multiple light sources, for reasons discussed in section 3. It is necessary to calculate reference light depending on the position of the light source. As shown in Fig. 4, the light wave distribution $R_p\left(x, y\right)$ of a pixel $(x, 0)$ on the hologram plane is expressed by

$$R_p(x, y) = R_0 \exp(jkx\sin\theta), \tag{7}$$

where R_0 is the amplitude of reference light. Moreover, when we define the position of a light source as (x', z), $\sin\theta$ is expressed by

$$\sin\theta = \frac{x'}{\sqrt{x'^2 + f^2}}. \tag{8}$$

2.3 Calculation for binocular system

As shown in Fig. 5, the reconstructed image in a binocular view must contain parallax information. CGHs for a binocular system are generated by applying a rotation matrix to the point-light source $P\left(x, y, z\right)$ that composes an object. The left coordinate system $\theta_L\left(x_L, y_L, z_L\right)$ is expressed by

$$\begin{pmatrix} x_L \\ y_L \\ z_L \end{pmatrix} = \begin{pmatrix} \sin\theta_L & 0 & \cos\theta_L \\ 0 & 1 & 0 \\ -\sin\theta_L & 0 & \cos\theta_L \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \tag{9}$$

where θ_L is the angle between the viewing direction of the left system and the z-axis. The right coordinate system is calculated similarly.

3. PROPOSED SYSTEM

We constructed a compact binocular holographic HMD. In this section, we describe the viewing zone expansion method we used and provide an outline of the holographic HMD.

3.1 Viewing zone expansion method with multiple light source

We use multiple light sources to expand the viewing zone. The viewing zone of light source 1 is defined as w_1 and that of light source 2 as w_2. By switching w_1 and w_2 according to the PD of the user, various users can observe the reconstructed images.

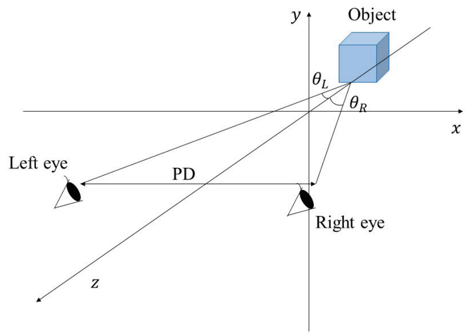


Fig. 5 Outline of the binocular system

Table. 1 Optical parameters

LCD	Pixel pitch	9.6 μm
	Resolution	1280(H) $\times$ 768(V) pixels
	Active area	12.29(H) $\times$ 7.37(V) mm
Wavelength	Red	638 nm
	Green	518 nm
	Blue	448 nm
Focal length of lens		60 mm

At the same time, as the position of the light source moves, the position of the reconstructed image also moves. Therefore, when the light source is switched, the CGH displayed on the LCD is also switched according to the position of the light source we use.

3.2 HMD system design

The binocular holographic HMD we constructed is shown in Fig. 6, where (a) shows the outline and (b) shows a photograph. The optical parameters are listed in Table 1. From Eqs. (1) and (2), the visual field angle θ and the size of viewing zone w are given by

$$\theta = 14.0[^\circ] \tag{10}$$

$$w_R = 4.0[\mathrm{mm}] \tag{11}$$

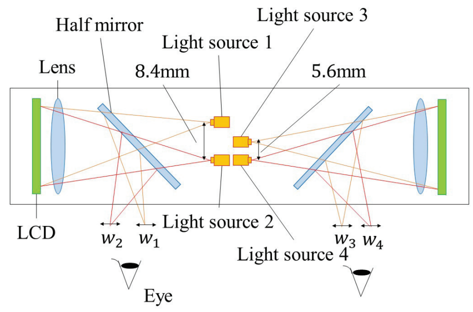
$$w_G = 3.2[\mathrm{mm}] \tag{12}$$

$$w_B = 2.8[\mathrm{mm}], \tag{13}$$

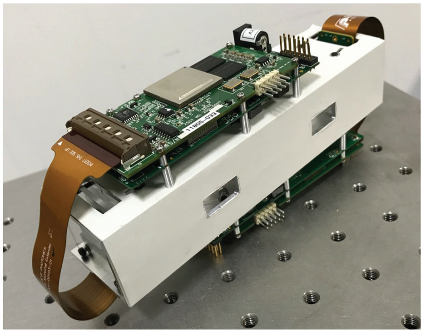
where w_R, w_G, and w_B are the viewing zones of Red, Green, and Blue. From Eq. (11) to (13), full color viewing zones w_1 to w_4 in Fig. 6(a) are given by

$$w_1 = w_2 = w_3 = w_4 = 2.8[\mathrm{mm}]. \tag{14}$$

In this paper, we designed the HMD so that users with a PD of 64 mm, which is the average male' PD, use light sources 2 and 3. From Eq. (14) and Fig. 6(a), the combinations of light sources and adjustable PDs are shown in Table 2.



(a) Outline



(b) Photograph

Fig. 6 Outline of holographic HMD system

Table. 2 Combinations of light sources and adjustable PDs

Number of light source	PD
2 and 4	66.8 to 72.4 mm
2 and 3	61.2 to 66.8 mm
1 and 4	58.4 to 64.0 mm
1 and 3	52.8 to 58.4 mm

4. EXPERIMENT

4.1 Confirmation of viewing zone expansion

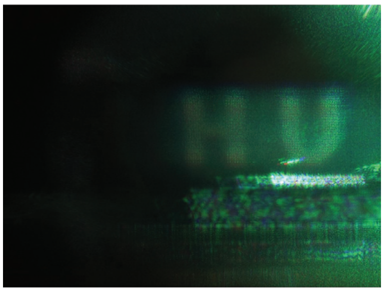
In this experiment, we confirmed that the viewing zone is expanded. Figure. 7 (a) shows the reconstructed image when light source 3 is used and (b) shows the image when the viewpoint is moved. As shown, the viewpoint is outside the viewing zone in this case. Figure. 7(c) shows the reconstructed image when the light source is switched to light source 4. As shown, the reconstructed image can be observed from the viewpoint where the reconstructed image can't be observed. From these results, we confirmed that the viewing zone is expanded.

4.2 Depth correction

In holography, we can observe reconstructed images at a free depth. As such, it is necessary that reconstructed images be displayed at an ideal depth. First, we measured the depth of reconstructed images using a camera. The depth of the reconstructed images is deeper than the ideal one (Fig. 8). Next, we recreated CGHs including in the results of this experiment and measured the depth

(a) Reconstructed image

(b) After moved viewpoint



(c) After switched light source

Fig. 7 Switching of the light source

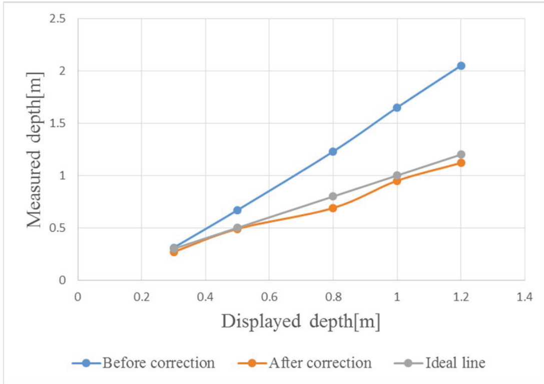


Fig. 8 Result of depth correction

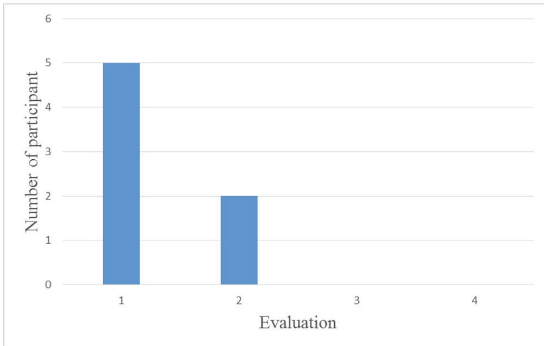


Fig. 9 Result of participant experiment

of the reconstructed images again. As shown in Fig. 8, those reconstructed images are displayed at almost the correct depth. The other light sources are also corrected similarly.

4.3 Participant experiment

In this experiment, use investigated how well the reconstructed images could observed. First, participants held the HMD at a position where the reconstructed image of the left eye was clearly visible. Second, they observed the reconstructed image of the right eye. According to how the reconstructed image looked on the right eye, the participants evaluated our binocular HMD. The results of this experiment indicate that most participants were able to observe the reconstructed images.

5. CONCLUSION

In this paper, we have proposed a viewing zone expansion method with multiple light sources and constructed a compact binocular holographic HMD using this method. Experimented results indicated that reconstructed images could be displayed at a free depth, thus expanding the viewing zone, due to this, most participants were able to observe the reconstructed images with both eyes. We have demonstrated that our binocular system has a wide viewing zone, which enables various users to observe the reconstructed images.

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