INVITED PAPER Special Section on Electronic Displays

Study on Compact Head-Mounted Display System Using Electro-Holography for Augmented Reality

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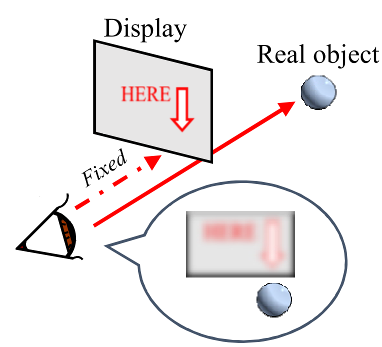
SUMMARY Head-mounted displays (HMDs) and augmented reality (AR) are actively being studied. However, ordinary AR HMDs for visual assistance have a problem in which users have difficulty simultaneously focusing their eyes on both the real target object and the displayed image because the image can only be displayed at a fixed distance from an user's eyes in contrast to where the real object three-dimensionally exists. Therefore, we considered incorporating a holographic technology, an ideal three-dimensional (3D) display technology, into an AR HMD system. A few studies on holographic HMDs have had technical problems, and they have faults in size and weight. This paper proposes a compact holographic AR HMD system with the purpose of enabling an ideal 3D AR HMD system which can correctly reconstruct the image at any depth. In this paper, a Fourier transform optical system (FTOS) was implemented using only one lens in order to achieve a compact and lightweight structure, and a compact holographic AR HMD system was constructed. The experimental results showed that the proposed system can reconstruct sharp images at the correct depth for a wide depth range. This study enabled an ideal 3D AR HMD system that enables simultaneous viewing of both the real target object and the reconstructed image without feeling visual fatigue.
key words: *head-mounted display, augmented reality, electro-holography, computer-generated hologram*

1. Introduction

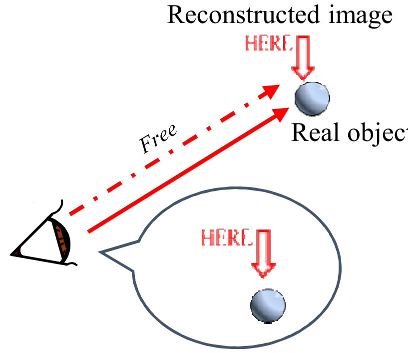
Display technologies such as head-mounted displays (HMDs), virtual reality (VR), and augmented reality (AR) are actively being studied. VR technology can display a virtual-world environment that feels realistic, and AR technology can display computer-generated images in the real world. These technologies are used in HMDs which are respectively called AR HMDs or VR HMDs. AR HMDs are especially expected to be made practicable because AR technology used in the real world is suitable for a variety of applications: surgery assistance in the medical field, digital reconstruction of famous historical structures in the cultural field, and so on. In fact, the studies on AR systems for route guidance and sightseeing guidance have been reported [1], [2].

Nowadays, AR HMDs are produced by several manufacturers. For example, EPSON MOVERIO AR smart glasses provide visual assistance. However, ordinary AR HMDs have a problem in which images can only be displayed at a fixed distance from a user's eye's in contrast to where the real object three-dimensionally exists as shown in Fig. 1 (a). Therefore, users have difficulty simultaneously focusing their eyes on both the real target object and the displayed image. For that reason, we considered incorporating a holographic technology, an ideal three-dimensional (3D) display technology, into an AR HMD system. By reconstructing the images at any depth using the technology, the problem with AR HMDs can be solved, and an ideal 3D AR system that enables simultaneous viewing of both the real target object and the reconstructed image without feeing visual fatigue can be enabled as shown in Fig. 1 (b). However, a few studies on holographic HMDs, which have had HMDs using a holographic technology, done so far with technical problems, and they have faults in size and weight as the holographic HMDs [3], [4].

In this paper, we propose a compact holographic AR HMD system. Using the developed system, we evaluated correctness of depth of reconstructed image, which is important for an 3D AR HMD system.



(a) Ordinary AR system



(b) Ideal AR system

Fig. 1 AR system.

Manuscript received February 28, 2017.
Manuscript revised June 1, 2017.
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DOI: 10.1587/transele.E100.C.965

2. AR System

An AR system can be a video see-through system or an optical see-through system [5]. In this section, we respectively describe the two see-through systems.

2.1 Video See-through System

In a video see-through system, the real world is captured into a computer as digital data by using a photographing device such as a camera, and an electronic device displays both the real information and the virtual information as shown in Fig. 2 (a). A video see-through system has the advantage of matching the real information with the virtual information easily because it can adjust the two sets of information in a computer. However, a video see-through system has problems in which the real-world information must be converted into 2D images in order to be displayed on an electronic device and the system structure is complicated. Moreover, there is a visual gap between the real view and the displayed view. Therefore, a video see-through system is not suitable for use in an ideal and compact AR system.

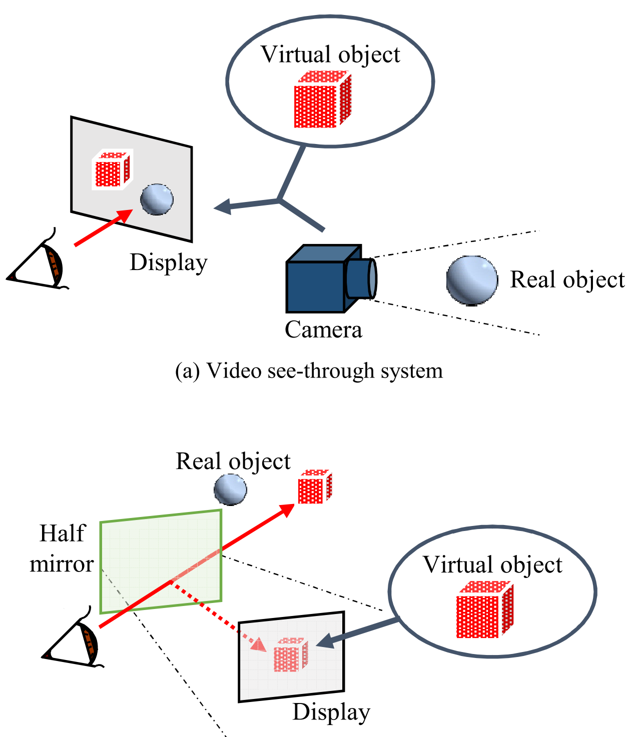
2.2 Optical See-through System

In an optical see-through system, we can directly view the real world with virtual images displayed by an electronic device through a half mirror or a beam splitter as shown in Fig. 2 (b). An optical see-through system has a problem in which a decline of visibility is caused by substantial differing in the brightness between the real world and the virtual object. However, we can view the real world three-dimensionally, and the system structure is simple in an optical see-through system. Therefore, an optical see-through system is suitable for use in an ideal and compact AR system.

3. Holography

In order for humans to perceive an object three-dimensionally, it is necessary to satisfy all the visual features: accommodation, vergence, and binocular parallax [6]. Holography [7] uses physical phenomena such as interference and diffraction of light, so it is an ideal 3D display technology satisfying all the human visual features in perceiving 3D images mentioned above. Therefore, holography makes it possible to enable an ideal 3D AR system.

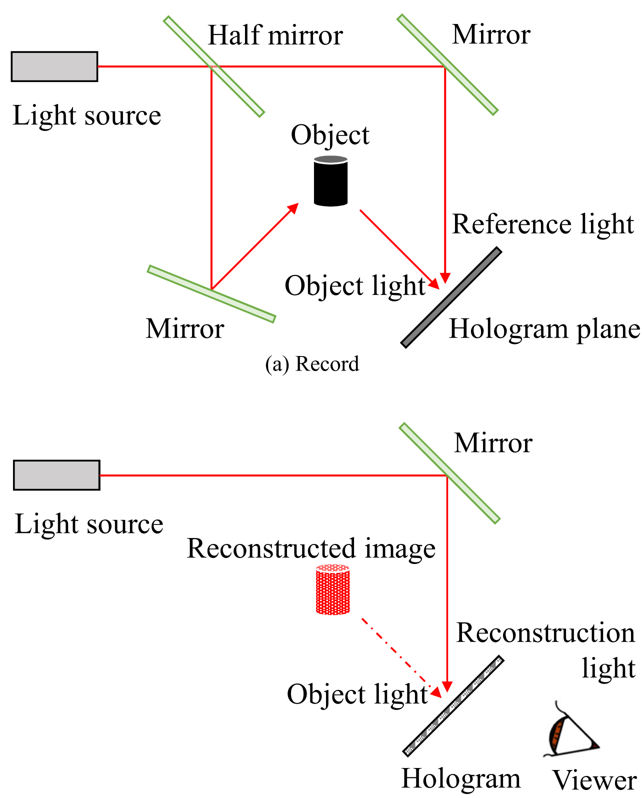
As shown in Fig. 3 (a), an interference pattern is recorded by interference of object light and reference light, where the object light is defined as light propagated from an object to a hologram plane, and reference light is defined as light irradiating a hologram plane directly. The recording medium is called a hologram. On the other hand, holographic images are reconstructed by diffraction on a hologram irradiated by reconstruction light as shown in Fig. 3



(a) Video see-through system

(b) Optical see-through system

Fig. 2 See-through method.



(a) Record

(b) Reconstruction

Fig. 3 Holography.

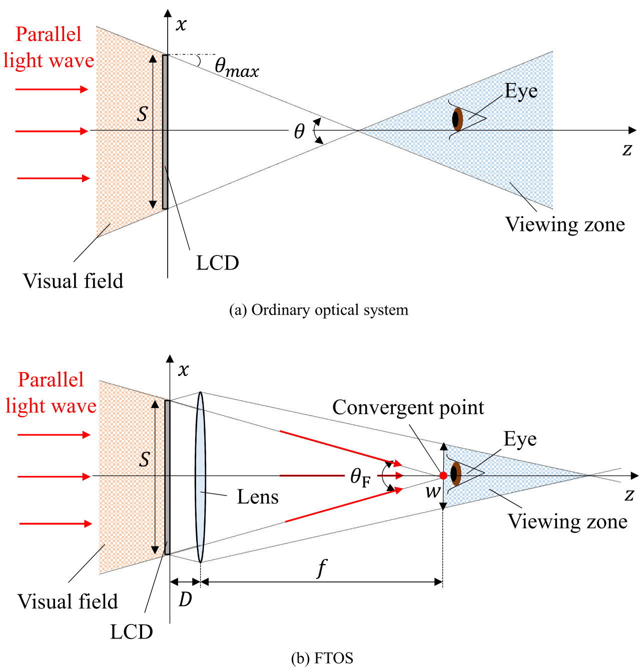


Fig. 4 Optical system in holography.

(b), where reconstruction light is defined as light with physical properties equal to the reference light used in the recording process. A holographic image reconstruction is dependent on the color of the light source. In the following subsections, we describe electro-holography and the hologram data used in this study.

3.1 Electro-Holography

Electro-holography is a holographic technology using an electronic device such as a liquid crystal display (LCD) to reconstruct holographic images, and the electronic device is used to display hologram data. Electro-holography can display holographic movies and be applied to telecommunication in contrast to analog holography.

As an optical system in electro-holography, an ordinary optical system and the Fourier transform optical system (FTOS) [8] are respectively shown in Figs. 4 (a) and (b). The FTOS is actually implemented by irradiating parallel light waves generated by using a lens and a point light source. However, the case of irradiating parallel light waves simply is shown in Fig. 4 (b) for convenience. In the case of arranging a pixel transmitting and not transmitting light alternately, the maximum diffraction angle θ_{max} on an electronic device is derived by the Huygens–Fresnel principle as shown in Fig. 5, and it is given by

$$2p \sin\theta_{max} = \lambda, \tag{1}$$

$$\theta_{max} = \sin^{-1}\left(\frac{\lambda}{2p}\right), \tag{2}$$

where p is the pixel pitch of the electronic device, and λ is the wavelength.

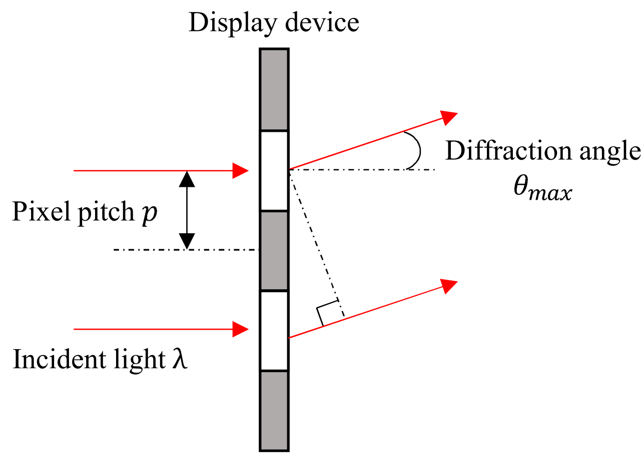


Fig. 5 Diffraction on electronic device.

In an ordinary optical system, the visual field angle θ depends on the maximum diffraction angle θ_{max} on an electronic device, and it is given by

$$\theta = 2\theta_{max}, \tag{3}$$

$$= 2\sin^{-1}\left(\frac{\lambda}{2p}\right). \tag{4}$$

As shown in Eq. (4), the visual field in an ordinary optical system greatly depends on a pixel pitch p of an electronic device. However, there is currently no electronic device having high resolution enabling a wide visual field. On the other hand, the visual field angle θ_F in the FTOS is given by

$$\theta_F = 2\tan^{-1}\left(\frac{S}{2f}\right), \tag{5}$$

where S is the size of the electronic device, and f is the focal length of the lens. The maximum viewing window size w in the viewing zone based on the FTOS, is given by

$$w = \frac{\lambda f}{p}. \tag{6}$$

As shown in Eq. (5), the visual field angle θ_F in the FTOS can be enlarged by the focal length f of the lens used in the optical system. In addition, the FTOS has the advantages of removing the 0-th order light and ghost images with a simple structure. It is suitable for an eyepiece-type holographic display such as a holographic HMD because it can be used to view larger holographic images very close to the user's eyes. For that reason, we use the FTOS in our proposed holographic AR HMD system.

3.2 Computer-Generated Hologram

As hologram data displayed on an electronic device, we use a computer-generated hologram (CGH). It is calculated by simulating wave propagation using a computer. In CGH calculation, all of the recording processes in holography are completed on a computer. Therefore, any object can be recorded as an interference pattern regardless of whether it is a real object or a virtual object such as a computer graphics (CG) model.

In this study, CGHs are calculated by the point-based method [9] shown in Fig. 6. This CGH calculation method is applicable to any object having a complicated shape because it regards an object as a cloud of point lights. When an object is composed of N point lights, the point-based method is calculated as follows. The propagation distance from the i-th point light $P_i(x_i, y_i, z_i)$ on the object to a pixel $P_h(x, y, 0)$ on the hologram plane is given by

$$r_i(x, y) = \sqrt{(x_i - x)^2 + (y_i - y)^2 + {z_i}^2}. \tag{7}$$

Using the propagation distance $r_i(x, y)$, the complex amplitude distribution $O(x, y)$ of the object light on the hologram plane is calculated by

$$O(x, y) = \sum_{i=1}^{N} \frac{a_i}{r_i(x, y)} \exp\{-j(kr_i(x, y) + \phi_i)\}, \tag{8}$$

where a_i is the amplitude of the i-th point light, k is the wavenumber, and ϕ_i is the initial phase of the i-th point light. The interference pattern on the hologram plane is calculated by simulating the wave propagation of reference light having physical properties equal to the reconstruction light used in the optical system with the complex amplitude distribution $O(x, y)$ of the object light, and CGHs are output as 2D image data.

Since the holographic images are reconstructed only at the convergent point of the reconstruction light in the FTOS, it is necessary to use the depth-free CGH calculation method [10] in the FTOS based on the lensless Fourier-transform method [11]. The hologram data with this method [10] are not the same as those of "Fourier Transform Holography" because the data are not Fourier transform of the object, and the optical system displays virtual images. Generally, such hologram data can be obtained by setting

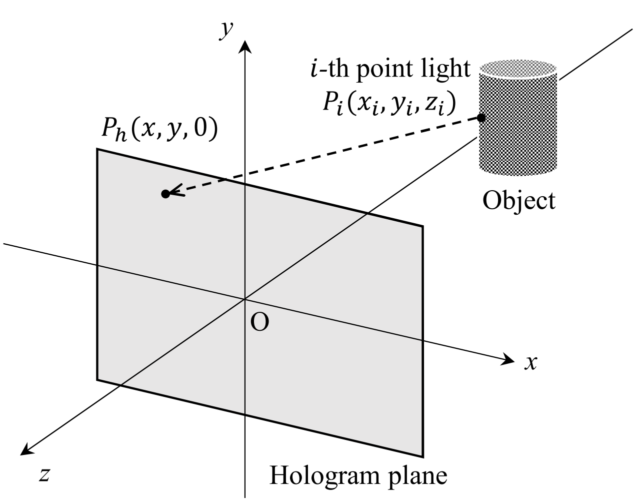


Fig. 6 Wave propagation using point-based method.

the reference light as a convergent spherical light. However, in this study, a parallel light is used as the reference light by the method [10] as described below. In the case of reconstructing the i-th point $P_i(x_i, y_i, z_i)$ on an object, all we have to do is to transform the point $P_i(x_i, y_i, z_i)$ into another point $P_0(x_0, y_0, z_0)$ by using the depth-free CGH calculation method. The point $P_0(x_0, y_0, z_0)$ is calculated by

$$z_0 = -\frac{fA}{f + A}, \tag{9}$$

$$x_0 = x_i z_0 B, \tag{10}$$

$$y_0 = y_i z_0 B, \tag{11}$$

where f is the focal length of the lens, and A and B are given by

$$A = \frac{z_i(f - D) + D^2}{z_i - D - f}, \tag{12}$$

$$B = \frac{A + D - f}{Af}, \tag{13}$$

where D is the distance between the lens and the electronic device.

Realistic representation is possible using the CGH calculation with the ray tracing method [8]. In this study, we assumed that the device was used as a visual assistant such as for work support. Therefore, we conducted the experiments by displaying only simple geometric patterns and characters.

4. Compact Holographic AR HMD System

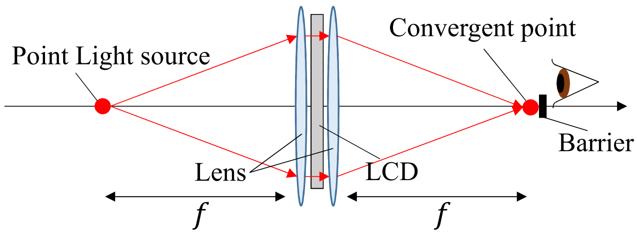
In this section, we describe the implementation of the FTOS and the structure of our compact holographic AR HMD system.

4.1 Implementation Method of FTOS

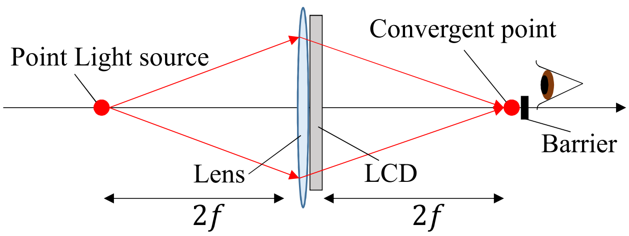
In this study, we considered implementing the FTOS simply to achieve a compact and lightweight structure suitable for an electro-holographic display. In this subsection, we describe the implementation method of the simple FTOS in contrast to the ordinary FTOS. While an ordinary FTOS is implemented by using two lenses and a point light source arranged at the focal point of the lens as shown in Fig. 7 (a), the simple FTOS in our system was implemented by using only one lens and a point light source arranged at the point equal to two times the focal length of the lens as shown in Fig. 7 (b). Using only one lens, the lens on the other side and the jig used for it are unnecessary, so the optical system becomes simpler. As a result, the optical system gets smaller and lighter, and becomes easier to adjust.

4.2 System Structure

Our compact holographic AR HMD system is shown in Fig. 8. Figures 8 (a) and (b) respectively show a photograph and the design of our system. The optical parameters are



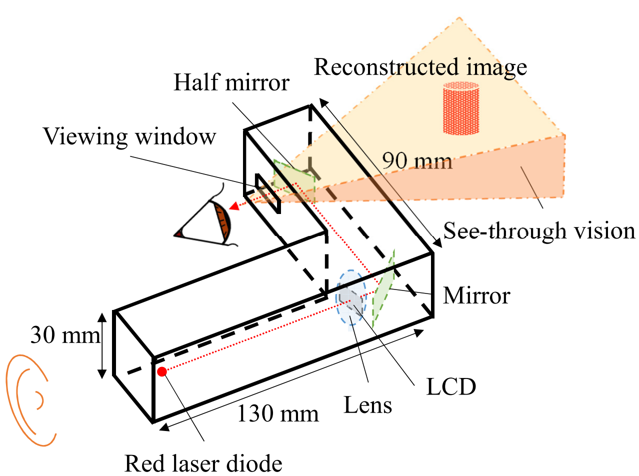
(a) Ordinary FTOS



(b) FTOS in proposed system

Fig. 7 FTOS implementation method.


(a) Photograph



(b) Design

Fig. 8 Compact holographic AR HMD system.

Table 1 Optical parameters.

LCD	Pixel pitch	12(H) × 12(V) μm
	Resolution	960(H) × 540(V) pixels
	Active area	11.5(H) × 6.5(V) mm
	Color/Mono	Red
	Gray level	8bits
Wavelength		650 nm
Focal length of lens		40 mm
Size		30(H) × 90(W) × 130(D) mm
Weight		120 g

listed in Table 1. The hologram data are calculated by using amplitude modulation. The LCD modulates the amplitude of the reference light with respect to the hologram data.

Our system is based on the FTOS using only one lens as described in Sect. 4.1. It is a monocular-type system composed of an LCD, a lens, a red laser diode (LD), a mirror, and a half mirror. The light emitted by the red LD is made to converge in front of the viewpoint through the lens by arranging the mirror and the half mirror. This structure is suitable for mounting on a person's head. The half mirror is arranged between the LCD and the viewpoint to display an AR scene in the real world as described in Sect. 2.2. The outside frame is made of aluminium. The size is 30(H) × 90(W) × 130(D) mm, and the weight is about 120 g. As shown here, our system implements a holographic HMD that is small and light. A monocular HMD with a compact and lightweight structure is suitable for a visual assistance device, and our system is designed for such a purpose. From Eqs. (5) and (6), the visual field angle θ_F and the viewing window size w are given by

$$\theta_F = 7.9 \text{ [deg]}, \tag{14}$$

$$w = 4.3 \text{ [mm]}. \tag{15}$$

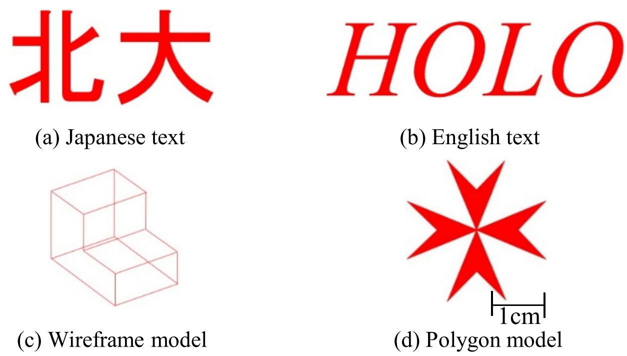
Equation (14) shows that our system has a wide visual field. It is the same as that of a 19-inch display at a depth of 2000 mm. The visual field is two times as wide as that in an ordinary optical system because our system is based on the FTOS. The viewing window size shown in Eq. (15) ensures natural eye accommodation because it is almost equal to human pupil size.

5. Experiments and Results

We experimentally evaluated the holographic images and AR scenes reconstructed by our system. In this section, we discuss the reconstruction performance and depth accuracy of our system.

5.1 Reconstruction of Holographic Images

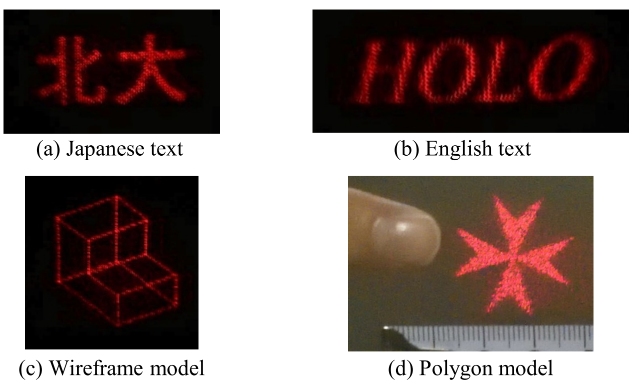
In this experiment, our system reconstructed the four data sets shown in Fig. 9 as holographic images to evaluate its reconstruction performance. The data were Japanese and English texts and wireframe and polygon models. We call the figure shown in Fig. 9 (d) formed from plane surfaces a polygon model for convenience in this subsection. The



(a) Japanese text (b) English text

(c) Wireframe model (d) Polygon model

Fig. 9 Original data.



(a) Japanese text (b) English text

(c) Wireframe model (d) Polygon model

Fig. 10 Reconstructed images.

four holographic images were reconstructed at a depth of 500 mm from the viewpoint.

We captured the four holographic images by using a camera arranged at the viewpoint. These photographs of the holographic images are shown in Fig. 10. The two holographic texts shown in Figs. 10 (a) and (b) and the two holographic models shown in Figs. 10 (c) and (d) were correctly reconstructed by our system. This shows that our system can reconstruct holographic images in various shapes using the point-based method described in Sect. 3.2 because it expresses sharp holographic images composed by a very small point light. As shown in Fig. 10 (d), the reconstructed image was bright enough to be seen in an office, and the image was reconstructed with correct size. The system can be used as an AR HMD for indoor use.

5.2 Depth Evaluation

In this experiment, our system reconstructed the two holographic images in the real world to evaluate the depth accuracy. The AR scene displayed by our system is shown in Fig. 11. The real objects arranged in the AR scene were a Landolt ring and a Maltese cross at a depth of 500 mm and 2000 mm. The holographic images were arrows with a numerical depth, and the CGHs were calculated in order for the holographic images to be reconstructed on the respective real objects. The two pairs of the real object and the holographic image were arranged at the same depth, respectively.

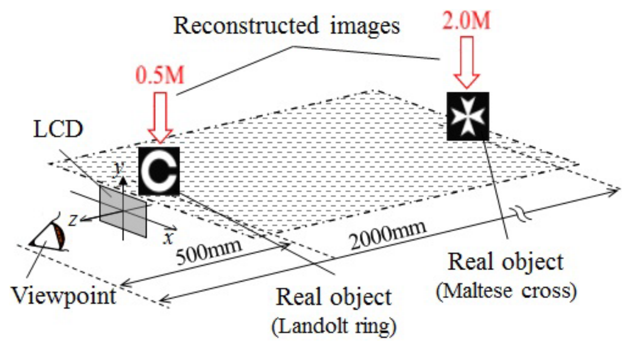
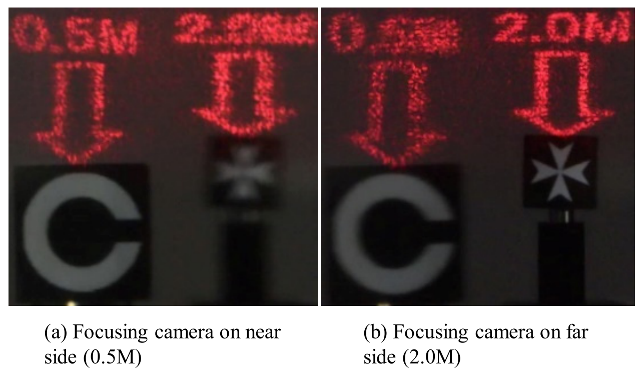


Fig. 11 Experimental environment.



(a) Focusing camera on near side (0.5M) (b) Focusing camera on far side (2.0M)

Fig. 12 AR scene.

We captured the AR scene by using a camera positioned at the viewpoint. The photographs of the AR scene are shown in Fig. 12. Fig. 12 (a) shows the case of focusing the camera near the viewpoint at a depth of 500 mm, and Fig. 12 (b) shows the case of focusing the camera far from the viewpoint at a depth of 2000 mm. In the two figures, we can see that the real object and holographic image focused by camera were cleared, and the other object and image were blurred. This shows that the two holographic images were correctly reconstructed at depths of 500 mm and 2000 mm, respectively. In other words, our system can reconstruct holographic images at the correct depth over a wide depth range.

6. Discussion

We successfully developed a small and lightweight holographic HMD system by using a lens with a short focal length. However, the use of the lens causes increasing the sensitivity of the installation error and the distortion of reconstructed images. It is possible to correct the installation error can be corrected by using the calibration method in the CGH calculation [12].

In addition, it takes too long time to calculate to CGH for practical application. A potential way to solve this problem is to use parallel computation on a graphics processing unit (GPU) [13]. A possible solution for CGH animation involving viewpoint movements such as those required in using a holographic HMD is also proposed [14]. Future work thus includes developing a fast CGH calculation method in order to achieve a practical holographic AR HMD system.

7. Conclusion

In this paper, we proposed a compact holographic AR HMD system with the aim of developing an ideal 3D AR system. Our system can reconstruct images at any depth differently from ordinary AR HMDs because it uses holographic technology. Therefore, our system can display an ideal 3D AR scene that enables simultaneous viewing of both a real target object and a reconstructed image without visual fatigue. In addition, our system has a compact and lightweight structure in contrast to conventional holographic HMDs. The experimental results showed that our system can reconstruct sharp images at the correct depth over a wide depth range. From the above, we confirmed that a holographic AR HMD system can be used as an ideal 3D AR system in the future. Development of an optical error correction method and a fast CGH calculation method are needed for this system to become practical.

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