Wide-Viewing Zone Electro-Holography System by Using Switching of Reconstruction Light

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ABSTRACT

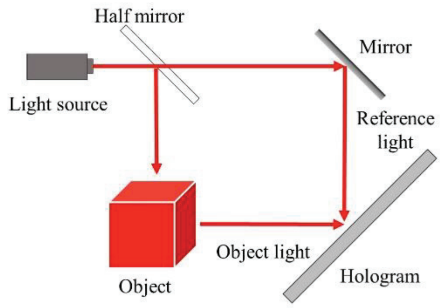
To solve the problem of narrow viewing field of electro-holography, we propose a design method of wide-viewing zone optical system that shifts the viewing zone with the movement of the observer. This optical system can be operated electronically without the need for special mechanical systems.

1 INTRODUCTION

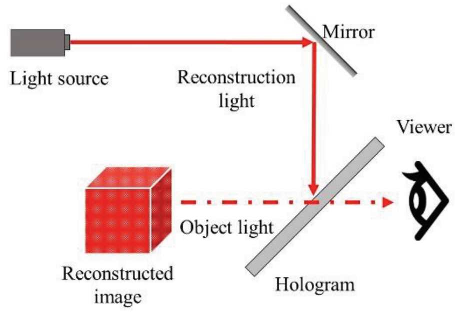
Recently, the technological development of displays has been focused on high resolution and thinness. Most of the current 3D display technologies can easily generate vivid 3D images, but they may cause discomfort and fatigue for observers. The reason is that they do not satisfy some of the physiological elements that humans need for stereoscopic perception. Holography has been proposed as the ultimate 3D display technique that satisfies all physiological elements for stereoscopic perception [1]. Since holography reconstructs light waves from an object, it is similar to observing a real object and can reconstruct a complete 3D image. However, they still have several problems, and one of which is the narrow viewing zone. There are some studies on enlarging the viewing zone. However, they have some disadvantages, such as not being able to touch the reconstructed image and having a small image [2], [3]. In this paper, we propose a design method for an optical system in which the visual field is electronically shifted according to the position of the observer, such as eye tracking, so that the reconstructed image, which is a real image, can be observed from a wide range of viewpoints.

2 Holography

Holography is a technique that uses interference and diffraction of light to record and reconstruct all light information from objects. In holography, the object light is defined as the light that propagates from an object to the hologram plane. The reference light used in the recording process is defined as the light that illuminates the hologram plane directly, and the reconstruction light used in the reconstruction process is defined as the light that has the same physical properties as the reference light used in the recording process. As shown in Fig.1(a), an interference pattern called a hologram is recorded due to interference between the object light and the reference light, and as shown in Fig.1(b), 3D images are reconstructed by diffraction on the hologram irradiated with the reconstruction light. The color of the 3D images reconstructed in holography depends on the light source.



(a) Record



(b) Reconstruction

Fig.1 Holography

2.1 Computer-generated hologram

Hologram data which are calculated by simulating the recording process of holography using a computer is called a computer-generated hologram (CGH). It can record any object 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, we use the point-based method [4] to calculate object light for CGH. This method is applicable to any object having a complicated shape because it regards an object as a cloud of point lights. When objects are composed of N point lights, the light wave distribution $O(x,y)$ of the object light on the hologram plane is calculated by

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

where r_i is the distance from the i-th point light source that has the amplitude a_i to the pixel (x, y) on the hologram plane, k is the wavenumber, and ϕ_i is the initial phase of the i-th point light. In addition to the object light, a reference light is required for the CGH calculation. In this study, parallel light is used as the reference light. The light wave distribution $R(x, y)$ of the reference light on the hologram plane is calculated by

$$R(x,y) = R_0 \exp(jkx \sin \alpha), \quad (2)$$

where R_0 is the intensity of the reference light, and α is the angle of incidence of the reference light to the hologram plane. After calculating the object light and the reference light on the hologram plane, the interference pattern of these light waves are calculated. The optical intensity distribution of the interference fringes $I(x, y)$ is described as

$$I(x,y) = |O(x,y) + R(x,y)|^2. \quad (3)$$

The optical intensity distribution is exported as image data and used as a hologram.

2.2 Electro-holography

Electro-holography is holography technology for displaying holograms on electronic devices such as a liquid crystal display (LCD) and reconstructing 3D images. Since the holograms are digital data, electro-holography can be animated by switching the holograms on the display in chronological order, making it suitable for transmission and replication.

2.3 Viewing zone

The viewing zone of electro-holography is the zone within which the reconstructed image can be observed. The angle at which the entire zone of the reconstructed image can be observed is called the viewing zone angle. The viewing zone angle θ is calculated by

$$\theta = \sin^{-1} \frac{\lambda}{2p}, \quad (4)$$

where λ is the wavelength, p is the pixel pitch of the electronic device. The viewing zone angle coincides with the maximum diffraction angle of the electronic device and is dependent on the pixel pitch, as shown in Equation (4).

3 PROPOSED METHOD

In this study, we propose a design method for electronic wide-viewing zone optical system using multiple reconstruction lights and $4f$ concave mirror optical system.

3.1 Multiple reconstruction lights

As shown in Fig.2, the viewing zone of the reconstructed image shifts depending on the angle of incidence of the reference light to the hologram plane. Multiple reconstruction lights with different incidence angles are arranged, and the reconstruction light is changed

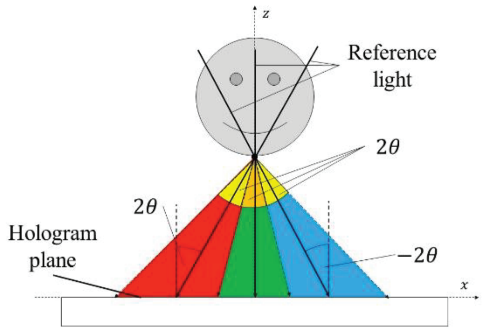


Fig.2 Proposed Viewing Zone

according to the position of the observer's eye. Then, the reconstructed image can be observed at a new position where it could not be observed by moving the eye. This means that the viewing zone has been enlarged. The incident angle of the reference light is changed by two times the maximum diffraction angle of the LCD in equation (2) which means $\alpha = 2\theta$ to eliminate unnecessary overlap in viewing area.

3.2 CGH calculation method

The CGH is calculated according to the incident angle α of the reference light. The number of holograms should be the same as the number of reconstruction light that is prepared. When n reconstruction lights are arranged, from the equation (2) and (3), the calculations of mth CGH are described as

$$R_m = \exp\{jkx \sin m\alpha\}, \quad I_m = |O + R_m|^2, \quad (5)$$

where $m = -\frac{n}{2}, \cdots, -1,0,1, \cdots, \frac{n}{2}$. The calculation of the object light is the same as the conventional method.

In addition, it is necessary to limit the computational area because aliasing occurs at high frequencies that exceed the sampling theorem of electronic devices. Denote the coordinates of an object point as (x_i, y_i, z_i) and a point on the hologram as (x, y, z), then the area limiting condition is described as

$$\left| \frac{1}{\lambda} \left(\frac{x - x_i}{\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}} - \sin \alpha \right) \right| < \frac{1}{2p}, \quad (6)$$

where λ is the wavelength, p is the pixel pitch of the electronic device and α is the angle of incidence of the reference light to the hologram plane.

3.3 $4f$ concave mirror optical system

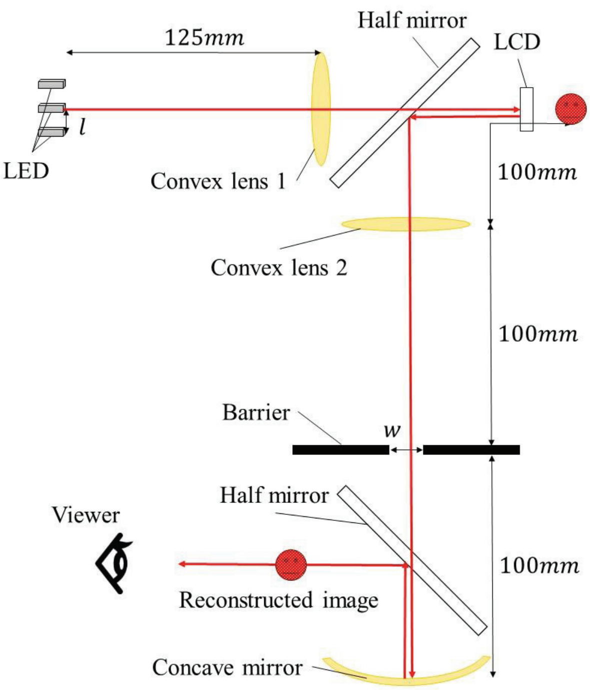
Since the pixel pitch of the display is not sufficiently narrow, electro-holography generates undesirable light that interferes with observation, such as conjugate images, higher-order images, and zero-order light, in addition to the reconstructed image. Therefore, all undesirable light is removed using a 4f concave mirror optical system with a single-sideband method [5], [6].

The single-sideband method removes the conjugate image by limiting the direction of the object light in CGH calculation process and separating the object light from the light that creates the conjugate image in holography reconstruction process.

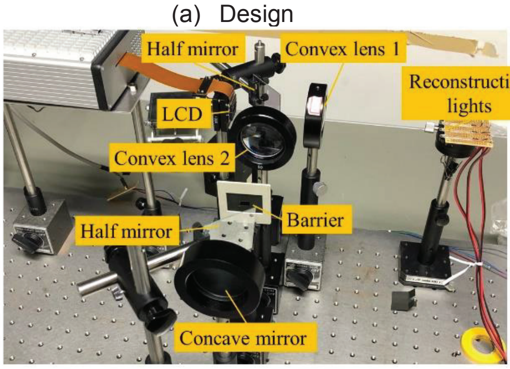
In this study, a 4f concave mirror optical system with a convex lens and a concave mirror arranged in sequence is used. The 4f concave mirror optics eliminates the parallel light and higher-order images caused by higher-order diffraction by placing a barrier at the focus of a convex lens. In addition, the light is reimaged by a concave mirror, so that the reconstructed image can be observed as a real image. Since the zero-order light is parallel light, this optical system removes the zero-order light regardless of the angle of incidence of the reconstruction light.

4 Experiment

Based on the design theory proposed in Section 3, we constructed the optical system, and it is confirmed whether the reconstructed image, from which the undesirable light is removed, is correctly observed for each reconstruction light.



(a) Design



(b) Photograph

Fig.3 Optical system

4.1 Optical system

The constructed optical system is shown in Fig.3, and the parameters of the optical system are shown in Table.1. In this experiment, three pieces of reconstruction light were used. Red LEDs were used for all three reconstruction lights. The intervals of the reconstruction light and the aperture size of the barrier is determined according to the parameters of the electronic device. The intervals of the reconstruction light are determined based on the maximum diffraction angle θ of the electronic device, which is calculated from the equation (4). The interval l of the reconstruction lights is calculated by

$$l = f_1 \tan 2\theta, \tag{7}$$

where f_1 is the focal length of convex lens 1. The aperture size of the barrier w is determined by

$$w = f_2 \tan \theta, \tag{8}$$

where f_2 is the focal length of convex lens 2. Since the ratio of the focal length of the concave mirror to the convex lens2 is 1:1, the size of the reconstructed image does not change. This optical system can be operated electronically without the need for special mechanical systems. The arrangement of the objects to be reconstructed in this experiment is shown in Fig.4.

4.2 Results

The images reconstructed by each reconstruction light are shown in Fig.5. The reconstructed images could be observed in all the reconstruction light, and the undesirable light was removed. In addition, the

Table. 1 Parameters of optical system

Pixel pitch of LCD		6.4×6.4[μm]
Number of Pixels		$1{,}920 \times 1{,}080$[pixels]
Refresh rate of LCD		180[Hz]
Wavelength of LED		624[nm]
Focal length	Convex lens 1	125[mm]
	Convex lens 2	100[mm]
	Concave mirror	100[mm]

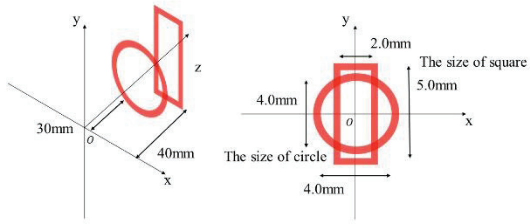
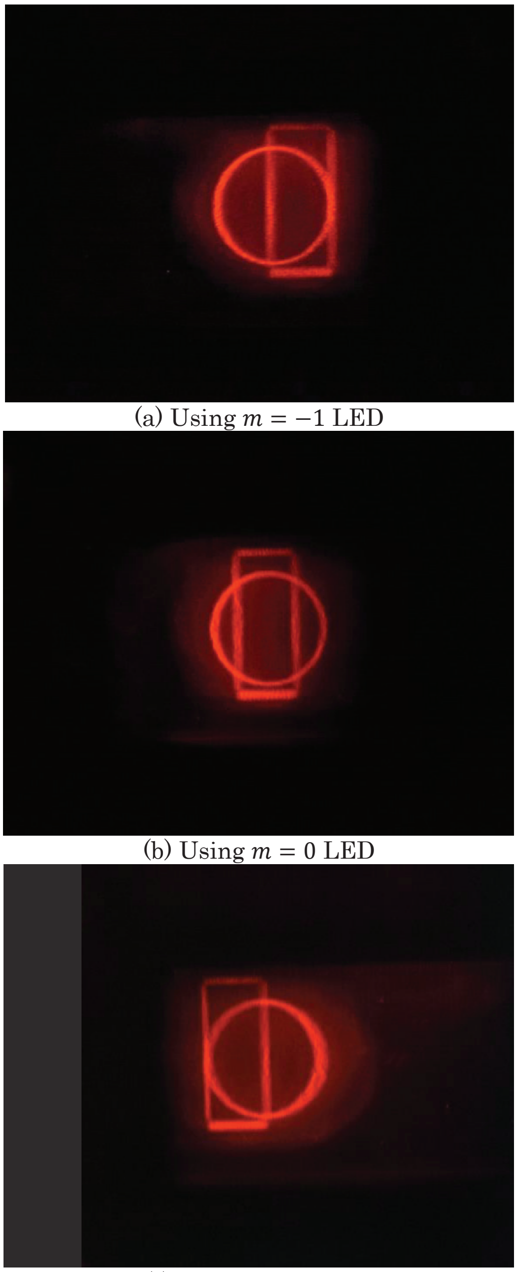


Fig.4 Arrangement of objects



(a) Using $m = -1$ LED

(b) Using $m = 0$ LED

(c) Using $m = 1$ LED

Fig.5 Reconstructed image

reconstructed image could be touched as a real image and did not change in size. This allows us to observe only the real image from a wide area, and we have achieved consistency in the fabrication of the optical system.

5 CONCLUSIONS

In this study, we proposed a method for designing a wide-viewing zone optical system that can electronically switch the reconstruction light, remove all undesirable light, and observe a real image with no change in size, as well as a method for making holograms. We constructed an apparatus to prove the validity of the theory of the proposed method. In the future, we will introduce eye tracking technology to create an optical system that automatically switches the reconstruction light according to the position of the eye, which will enable us to realize a wide viewing range electronic holography.

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