Integral 3D Display System Using Eye-Tracking Technology

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ABSTRACT

We propose an integral 3D display system using eye-tracking technology. The proposed design achieves a viewing angle of 81.4° in the horizontal direction, 47.6° in the vertical direction, and twice the light ray density in both the horizontal and vertical directions compared with that of the conventional design.

1 Introduction

An integral three-dimensional (3D) display is an 3D imaging technology based on the principle of integral photography proposed by Lippmann [1]. It has full parallax and can reproduce continuous and natural 3D images in the depth direction [2]. This 3D display is a type of light field display that reproduces light rays in space that are equivalent to the light emitted from a real object by combining an elemental image array (EIA) and the corresponding lens array. It is assumed that "vergence-accommodation conflict," which causes visual fatigue in the binocular stereoscopic display, does not occur, in principle, in the integral 3D display [3]. Therefore, it is expected to be applied in industry as a future 3D display system.

Integral imaging reproduces many parallaxes and requires the use of a display device with many pixels and a narrow pixel pitch for high-performance displays [4]. For this reason, improving display performance with a configuration that includes only a display and a lens array is difficult owing to limitations of the display performance. Therefore, we propose a method for enhancing the viewing zone and depth range of the reproduced 3D image using eye-tracking technology and dynamically controlling the optical viewing zone (OVZ) formed by an EIA and a lens array. We also propose an OVZ formation and lens array arrangement suitable for a display system with an eye-tracking function [5].

2 Proposed System

2.1 System Configuration

Figure 1 shows the comparison between conventional and proposed designs. In general, integral 3D images are reproduced by placing a lens array in front of a device that displays an EIA. In the conventional design, because multiple viewers are available simultaneously, a wide OVZ must be considered using a lens array with a short focal length, as shown in Fig. 1(a). Therefore, the light ray density is low, with a narrow depth range.

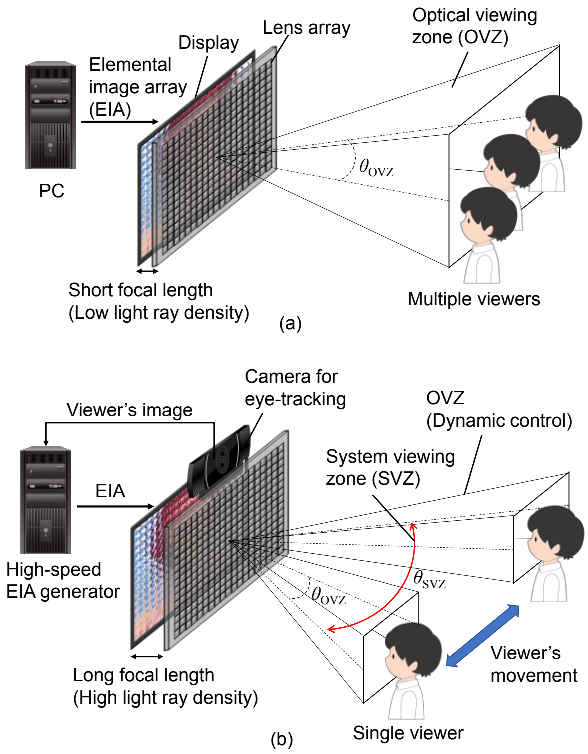

Fig. 1 System comparison between (a) the conventional design (without eye-tracking), and (b) the proposed design (with eye-tracking)

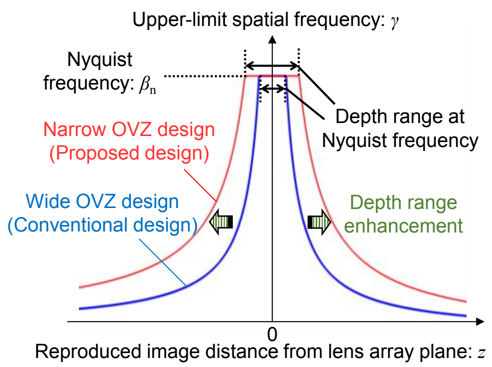

Fig. 2 Trade-off relationship between OVZ and depth range

As shown in Fig. 1(b), the proposed design uses a lens array with a long focal length to limit the display to a single user. Therefore, as light ray density increases, depth range is enhanced. Moreover, the OVZ is dynamically controlled using eye-tracking technology to change the EIA in accordance with the viewer's eye position, and a wide system viewing zone (SVZ) can be formed, as shown in Fig. 1(b).

Figure 2 shows the trade-off relationship between the OVZ and depth range. As shown in the following equation, the upper-limit spatial frequency γ in the integral 3D display is indicated by the smaller value of the viewing spatial frequency β and Nyquist frequency β_n [4].

$$\beta = \frac{f}{2p}\frac{(L-z)}{|z|}, \quad (1)$$

$$\beta_n = \frac{L}{2P_l}, \quad (2)$$

$$\gamma = \min[\beta, \beta_n], \quad (3)$$

where L is the viewing distance, z is the distance from the lens array to the display position of the 3D image, f is the focal length of the lens array, p is the pixel pitch, and P_l is the lens pitch. An OVZ angle θ_{OVZ} is computed as follows:

$$\theta_{OVZ} = 2\arctan\left(\frac{e}{2f}\right), \quad (4)$$

where e is the size of the elemental image.

The OVZ angle θ_{OVZ} decreases while the viewing spatial frequency β increases by increasing the focal length f of the lens array. Consequently, depth range is enhanced.

The working procedure of the proposed system is described as follows. First, the eye position of the viewer is acquired using a camera for eye-tracking installed above the display panel. Next, the EIA is generated such that the center of the OVZ is at the center of both eyes. Finally, the generated EIA is displayed on the display panel. These steps are repeated for each frame.

2.2 Real-Time Generation of EIA According to Eye Position

As shown in Fig. 3, a virtual camera array composed of multiple cameras is placed in virtual space, and a 3D model is shot from various directions to obtain multi-viewpoint images. Pixel mapping is then performed for these images to generate an EIA [6]. In pixel mapping, processing is accelerated by performing parallel processing using a graphics processing unit (GPU). The EIA is rendered by moving the virtual camera array dynamically such that the center of the virtual camera array is consistently at the center of both eyes. Rendering speed depends primarily on the number of virtual cameras. In the case of 16 cameras placed horizontally and 4 placed vertically, the frame rate was approximately 62.6 fps for a scene with approximately 2.6 million polygons. A PC with an Intel Core i7-7800X 3.50-GHz CPU, 64-GB memory, and an Nvidia Quadro P6000 GPU was used. The EIA rendering pipeline, and the EIA according to the viewpoints are shown in Figs. 4 and 5, respectively.

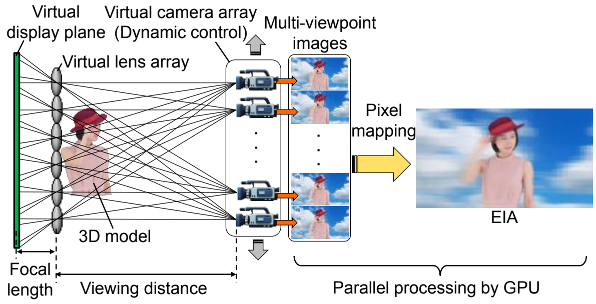

Fig. 3 High-speed generation of EIA based on eye position

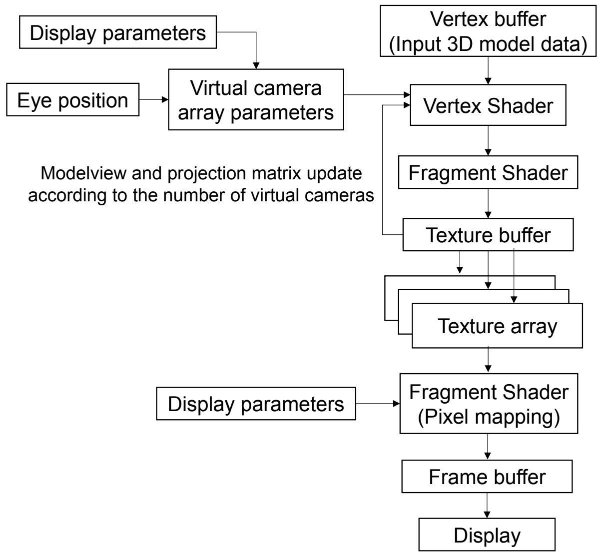

Fig. 4 EIA rendering pipeline

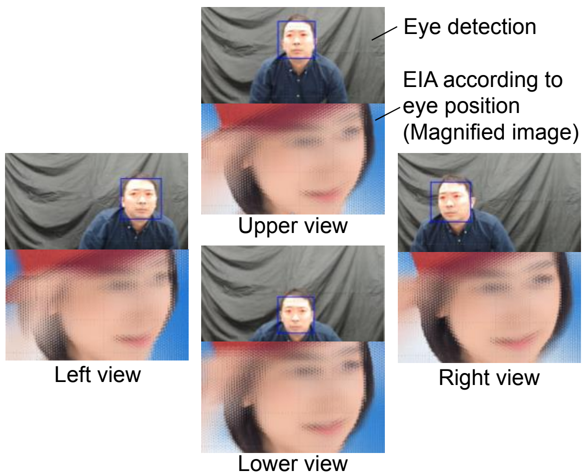

Fig. 5 EIA based on viewpoints

2.3 OVZ Formation Suitable for Eye-Tracking Integral 3D Display

In a display with eye-tracking function, the eyes fall out of the OVZ owing to an error in eye detection or system latency when the viewer looks at the display while moving, and crosstalk occurs. To solve this problem, a sufficient margin outside the OVZ to cover both eyes was provided in the OVZ formation. Because the eyes are in the horizontal direction, a wide OVZ design in the horizontal direction reduces the effects of eye detection error and system latency. In addition, as the EIA shape (aspect ratio) and OVZ match, an OVZ suitable for display with an eye-tracking function can be formed by designing the lens array arrangement.

When using a honeycomb structure lens array at 0° rotation, as shown in Fig. 6(a), the aspect ratio of the OVZ is $2:\sqrt{3}$ (horizontal:vertical). Conversely, when used at 30° rotation, as shown in Fig. 6(b), the aspect ratio of the OVZ becomes $2\sqrt{3}:1$, which is horizontally long [7]. In terms of the relationship between OVZ and the viewer's movement, the horizontally widened OVZ is more suitable for a display with an eye-tracking function, as shown in Fig. 6, because the occurrence of the crosstalk can be reduced. Therefore, a honeycomb structure lens array rotated by 30° was used in the prototype equipment.

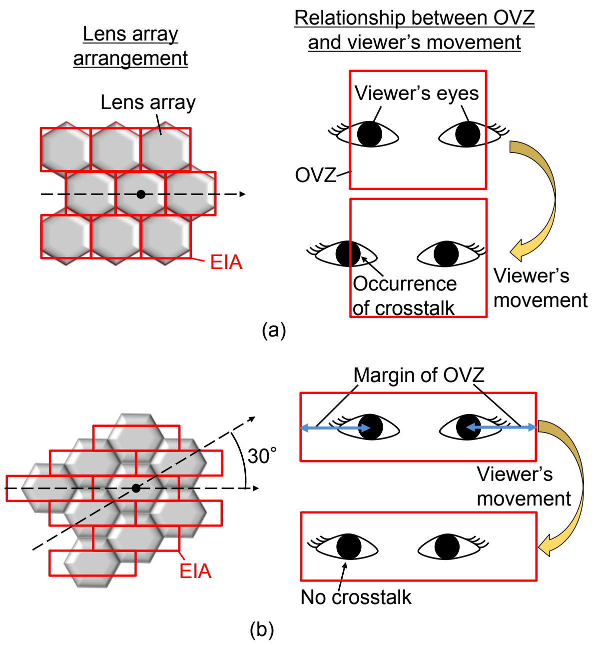

Fig. 6 Relationship between OVZ and viewer's movement when honeycomb structure lens array is rotated by (a) 0° and (b) 30°

3 Construction of Prototype Equipment

To conduct an evaluation experiment, prototype equipment using a high-pixel-density display was constructed, as shown in Fig. 7. A liquid crystal display (LCD) panel with a pixel density of 457.7 ppi, 4K (3840 × 2160) resolution, and a 9.6-in diagonal was used. For comparative experiments, we designed two types of lens arrays: conventional and proposed designs. Table 1 lists the specifications of the lens array. The lens array of the conventional design has a focal length of 1.0 mm and a square arrangement of 0° rotation. Conversely, the lens array of the proposed design has a focal length of 2.0 mm and a honeycomb arrangement of 30° rotation. As described in Section 2.3, a lens array with less crosstalk due to viewer's movement was designed to form a horizontally widened OVZ.

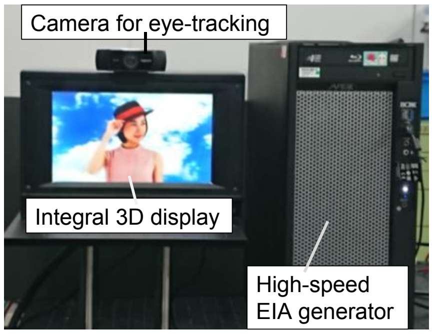

Fig. 7 Prototype equipment

Table 1 Comparison of lens array designs

	Conventional design	Proposed design
Lens pitch	0.5 mm	0.5 mm
Focal length	1.0 mm	2.0 mm
Lens arrangement	Square (0° rotation)	Honeycomb (30° rotation)
Lens shape	Square	Hexagonal
Number of EIA	426 (H) × 239 (V)	246 (H) × 480 (V)

4 Evaluation of Viewing Zone and Depth Range of Reproduced 3D Image

An evaluation experiment on the viewing zone was conducted using the prototype. Figure 8 shows the difference of the viewing zone between the conventional and proposed designs. In the conventional design, the horizontal and vertical viewing angles were 28.2° and 28.2°, respectively, whereas in the proposed design, these angles were 81.4° and 47.6°, respectively. The viewing zone was significantly enhanced using eye-tracking technology.

An experiment using a test chart was conducted to quantitatively evaluate the improvement in the depth range of the reproduced 3D image. Figure 9 shows the reproduced image of the test chart at a depth of 40 mm from the plane of the lens array for the conventional and proposed designs. In the conventional design, aliasing occurred at a spatial frequency of approximately 2.6 cycles per degree, whereas in the proposed design, aliasing did not occur up to a spatial frequency of approximately 5.2 cycles per degree. The design of a lens array with twice the focal length doubles the light ray density and enhances the depth range by a factor of approximately two.

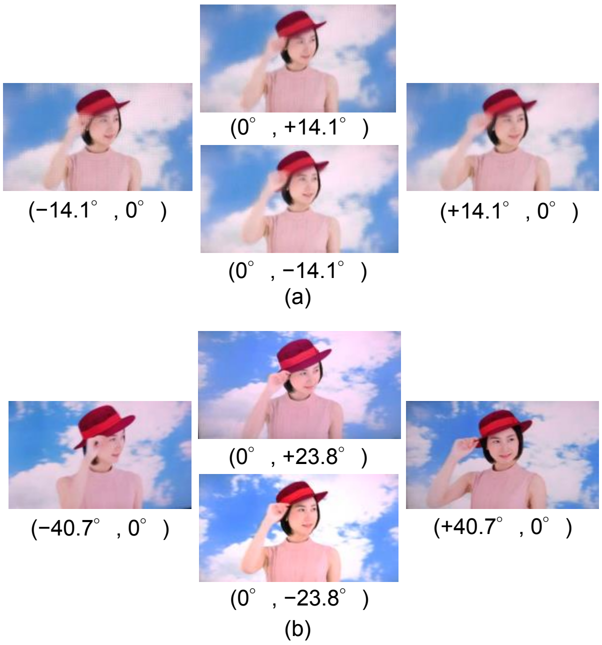

Fig. 8 Difference of viewing zones between (a) conventional and (b) proposed designs

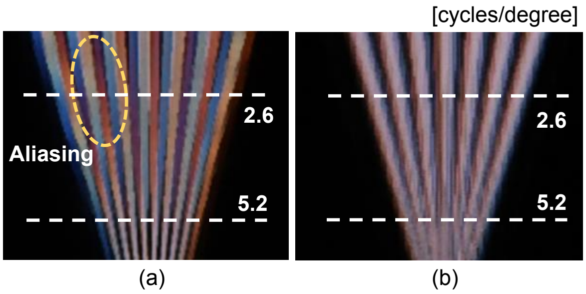

Fig. 9 Reproduced image of test chart at depth of 40 mm from lens array plane in (a) conventional and (b) proposed designs

5 Conclusions

In this paper, we proposed a method to enhance the viewing zone and depth range of integral 3D images by using eye-tracking technology. We constructed a system that dynamically controls the OVZ by generating an EIA in real time according to the viewer's eye position. We also proposed a lens design that reduces the occurrence of crosstalk due to the viewer's movement by forming a horizontally widened OVZ. As a result of constructing prototype equipment of the conventional and proposed designs and conducting a comparative experiment, the viewing zone was expanded by the eye-tracking technology. In addition, depth range was enhanced using a lens array with a longer focal length than that in the conventional design. In this manner, the proposed system was designed to improve the viewing zone, depth range, and crosstalk in a well-balanced manner. Because the device configuration is relatively straightforward, it is expected to be implemented as a 3D display for personal use in the future. Moreover, as an advanced version of this method, we also proposed a method that further increases light ray density by further narrowing an OVZ using a combination of a time-division display and eye-tracking technology [8]. In this manner, we aim to improve image quality and proceed with research and development toward the practical application of 3D video services on mobile terminals, such as smartphones and tablets.

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