Improvement of Field of View in Light-Field Head-Mounted Display by Displacing Elemental Images

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ABSTRACT

Causing discomfort and visual fatigue, vergence-accommodation conflict in head-mounted displays (HMD) is a major challenge. Recently, light-field HMD (LFHMD), which reconstructs rays from three-dimensional (3D) objects utilizing a microlens array, has been explored to solve this problem, but the field of view (FOV) of an LFHMD is narrow owing to the limitation of the display size and the long optical path length. We propose an LFHMD for a virtual reality device. In this study, a 5.5-inches 4K display panel is applied, and an elemental image is displaced from the back of the corresponding microlens. We confirmed the improvement of the FOV via simulation and experiment.

1 INTRODUCTION

Light-field head-mounted display (LFHMD) has the potential to resolve the vergence-accommodation conflict, which may cause discomfort and visual fatigue [1,2]. Many approaches applying light field to HMD using a microlens array have been reported [3-5]. The performance as an LFHMD device depends on the resolution, depth of field (DOF), and field of view (FOV). The resolution and the DOF are improved by applying a high-resolution microdisplay and a tunable lens [6]. However, the issue of a narrow FOV has persisted. This results from the small size of the reconstructed three-dimensional (3D) scene, which is due to the microdisplay and the diameter of optical elements such as an eyepiece or a tunable lens. Besides, a long-distance optical path for implementing an optical see-through also causes a narrow FOV. Herein, we propose a new method to improve the FOV by configuring the optical design for the use of a virtual reality device. A 4K flat display panel with 5.5 inches was applied, and an elemental image was displaced right behind the corresponding microlens to reduce the distance between the eyepiece and the eye. We confirmed the increase in FOV through simulation and experiment.

2 CONSTITUTION OF LFHMD AND PROPOSED METHOD

2.1 Image Formation Process of LFHMD

Figure 1 shows the schematic model of the LFHMD. An LFHMD consists of a display, a microlens array, and an eyepiece. A microlens array is arranged at a larger distance from the display panel than its focal length. The light rays emitted from the pixels of a display panel pass through a microlens array and intersect to form the intermediate image. It is magnified by an eyepiece, and we can observe the reconstructed 3D image. Light rays emitted by a point light source on the display converge on the intermediate image plane after propagated through the microlens array. The rays also converge after propagating through the eyepiece on the virtual image plane, which implies that the spatial resolution of the 3D image is higher close to the virtual image plane.

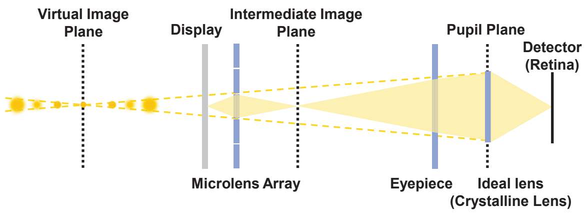

Fig. 1 Schematic model of LFHMD

2.2 Processes of Generating Elemental Image and Retinal Image

Figure 2 shows the process of image generation of the LFHMD. The image source of the LFHMD, which contains information, is called the elemental images. The elemental images are rendered by the optical ray-tracing method. The optical path is calculated by tracing rays that are emitted from the pixels, go through the microlens array and eyepiece and arrive at the pupil plane. The ray is retroreflected to determine whether it intersects with 3D objects. If this takes place, the pixel stores the color of the intersected point of the 3D object.

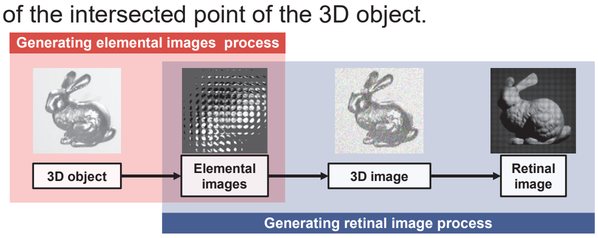

Fig. 2 Process of image generation

The image is reconstructed by the LFHMD, and we can observe the image through it. When the eye is cued to accommodate at the depth of the virtual image, the focused image is formed on the retina as a retinal image. In this study, the optical simulation software "OpticStudio" (Zemax, LLC) was used for generating the image. A display, a microlens array, and an eyepiece were arranged virtually the way they are for rendering the elemental image. Additionally, an ideal lens imitating a crystalline lens and a detector imitating a retina were added. Rays originating from the elemental images proceeded through the optical elements in random directions and generated a light intensity distribution on the detector. We evaluated the FOV from the retinal image. The parameters and arrangements of the display and optical elements are shown in Table 1 and Table 2.

Table 1 Specifications

Display	Resolution (pixels)	3840 (H) × 2160 (V)
	Size (inch)	5.5
Lens array	Pitch (mm) p_{array}	1.38
	Focal length (mm) f_{array}	8.85
	Arrangement	Delta
Eyepiece	Diameter (mm) d_{eye}	60
	Focal length (mm) f_{eye}	100
Eye	Pupil diameter (mm)	6

Table 2 Variables of the distance

Display−Microlens array (mm)	a	12.2
Microlens array−Intermediate image plane (mm)	b	32.3
Intermediate image plane−Eyepiece (mm)	c	90.9
Eyepiece−Virtual image plane (mm)	d	1000
Eyepiece−Pupil plane (mm)	e	20.0–100.0

2.3 Proposed Method

Elemental images are arranged in such a way that a ray from the center of each elemental image, passing through optical elements, intersects at the center of the pupil plane so that all elemental images are seen at the pupil plane. Although each elemental image was immediately behind the corresponding microlens in the previous studies [5,6], here, it is displaced from the position to widen the field of view for virtual reality (Fig. 3). This causes the pupil plane to move closer to the eyepiece, and the gap between the eyepiece and the pupil plane reduces. The displacement between the center of an elemental image and the optical axis y_{elem} is considered in the following equation:

$$y_{elem} = y_{eye} + \left(1 + \frac{a}{b+c}\right)\left(y_{array} - y_{eye}\right) \tag{1}$$

where a, b, and c are the gaps between a display and a microlens array, a microlens array and an intermediate image plane, and an intermediate image plane and an eyepiece, respectively. y_{array} is the displacement between the center of a corresponding microlens and the optical axis, and y_{eye} is the displacement between the optical axis and the intersection point between the ray and the eyepiece. They are as follows,

$$y_{array} = \frac{n}{2} p_{array} \tag{2}$$

$$y_{eye} = -\frac{s y_{array}}{1-t-s}, s = \frac{f_{eye}}{b+c}, t = \frac{f_{eye}}{e} \tag{3}$$

where n is the number of the microlens and p_{array} is the pitch of the microlens array. The microlens array is configured in a delta arrangement, and p_{array} in the horizontal and vertical directions are equivalent to p_{array} and $\sqrt{3}/2p_{array}$, respectively. f_{eye} is the focal length of the eyepiece. Pixels within the microlens radius from the center position of the elemental image are assigned to the same elemental image.

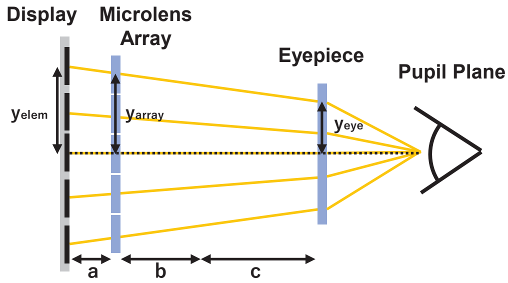

Fig. 3 Arrangement of displaced elemental images

2.4 Field of View of LFHMD

We define the FOV of the LFHMD as the area of the reconstructed 3D object on the virtual image plane. The FOV is determined by the size of the reconstructed 3D object y_{image} and the diameter of the eyepiece d_{eye}. Therefore, the FOV θ is given by:

$$\theta = 2\arctan\left[\min\left(\frac{y_{image}}{d+e}, \frac{d_{eye}}{2e}\right)\right] \tag{4}$$

Because the reconstructed 3D object is the magnified intermediate image by the eyepiece, its size y_{image} is given by

$$y_{image} = \frac{d}{c} y_{inter} \tag{5}$$

The size of the intermediate image y_{inter} is calculated by the elemental image at the far end of the display (Fig. 4). A microlens forms a real image of an elemental image on the intermediate image plane. The size of the intermediate image is the sum of the position of the ray emitted from the center of the elemental image on the intermediate image plane and the size of the intermediate image, is given as follows.

$$y_{inter} = y_{eye} + \frac{c}{b+c}\left(y_{array} - y_{eye}\right) + \frac{b}{a}\frac{p_{array}}{2} \tag{6}$$

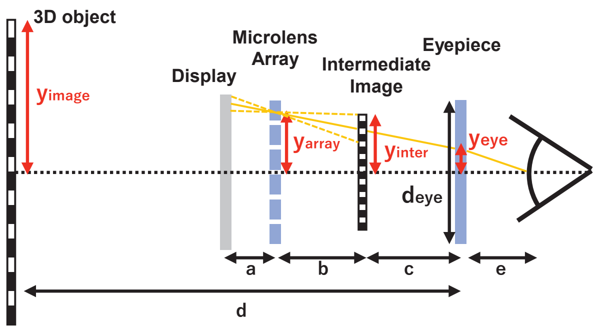

Fig. 4 Size of 3D object and intermediate image

3 EXPERIMENTS AND RESULTS

We evaluated the FOV from the simulated retinal image. A 3D plane with a graduated texture was placed 1000 mm from the eyepiece. The focal length of the crystalline lens is adjusted to focus the rays from the 3D plane on to the detector. Figure 5 shows the texture used in the simulation and the retinal images generated at different pupil plane positions. When the gap is less than 57 mm, all reconstructed 3D objects can be seen, but it becomes smaller as the distance between the pupil plane and the eyepiece decreases. When the gap is 57 mm or more, only a part of the reconstructed 3D object can be seen because of the limitation of the eyepiece diameter. In the design of previous study [6], the FOV is limited, as shown in Fig. 5 (d), but it was improved by the proposed method, as shown in Fig. 5 (b) and (c).

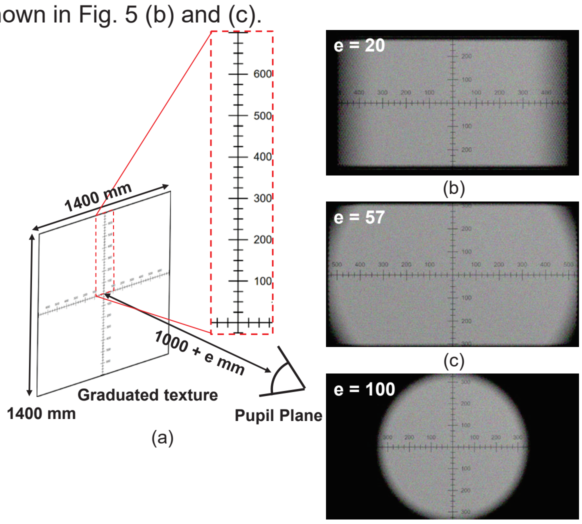

Fig. 5 (a) Graduated texture and (b) – (d) simulated retinal images

Figure 6 shows the FOV at different gaps between the eyepiece and pupil plane. The solid line represents Eq. (4), and points represent the values calculated from the scale of the retinal images. The equation and simulation results have close values. The FOV in the horizontal direction is maximum at e = 57 mm and that in the vertical direction is maximum at e = 91 mm.

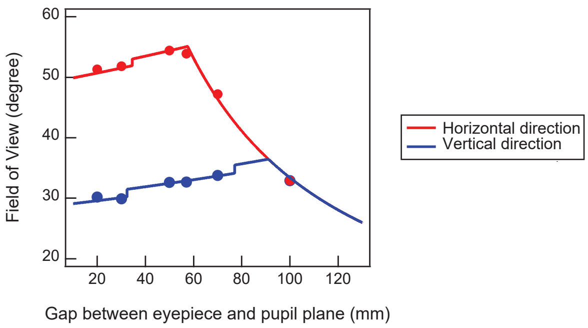

Fig. 6 FOV at different gaps between eyepiece and pupil plane

As a proof-of-concept, we developed a monocular prototype on an optical bench, as shown in Fig. 7 (a). The parameters of the display, the microlens array, and the eyepiece have the same values, as shown in Table 1. Fig. 7 (b) shows the photograph of the prototype at e = 57 mm by placing the camera at the pupil plane. The captured image is almost the same as the simulation image, but the discontinuous image disorder occurred around the captured image. The crook of the microlens array and the optical aberration may cause it because in the simulation, the ideal lens is adopted to the microlens array and the eyepiece.

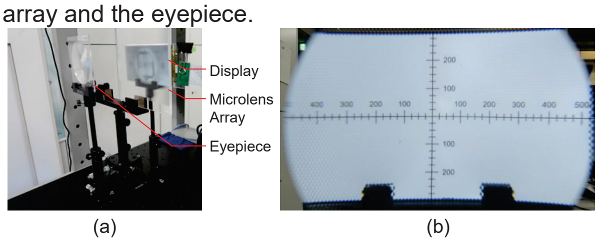

Fig. 7 (a) Monocular LFHMD prototype on optical bench and (b) photograph at e = 57 mm

4 CONCLUSIONS

We have configured the optical design of an LFHMD to improve the FOV for use in virtual reality applications. The gap between the eyepiece and the pupil plane could be reduced by the proposed method. The optimum position was investigated by the optical simulation and the theoretical equation. The prototype was demonstrated on the optical bench as a proof-of-concept. We will further examine the compensation of the crook and the optical aberration and a new arrangement of optical elements for device downsizing.

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