Wide-Field-of-View Head-mounted Display Employing Optical Coupling Method on Retina Using Four Display Panels and Eyepieces

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ABSTRACT

We investigated a wide-field-of-view (wide-FoV) head-mounted display (HMD) employing optical coupling on the retina using multiple display panels and eyepieces. We aimed to realize a wide-FoV HMD for high-resolution virtual reality (VR) images to enable users to feel a sense of realism toward future broadcast media services. We designed an optical system of a wide-FoV HMD by simulating the optical ray from a display to the retina using a human-eye optical model. We experimentally developed a 180° wide FoV of an optical system for an HMD using four liquid crystal display panels and eyepieces and evaluated the FoV using an omnidirectional camera. We also prototyped software to render binocular images from high-resolution VR movies for four display panels and evaluated the system.

1 INTRODUCTION

Since 4K and 8K satellite broadcast services started in Japan in December 2018, ultrahigh-definition television images with 4K and 8K horizontal pixels were provided to viewers with a stronger sense of realism and a sense of being present [1]. Meanwhile, the head-mounted display (HMD) with some virtual reality (VR) images, including omnidirectional content, is also provided to viewers with an immersive sense and is expanding its market [2]. However, the current commercial HMD devices do not have sufficient spatial resolution and FoV for human-eye perception because their display panels are close to the eye and the view through an eyepiece is expanded. Commercial HMDs generally have a field-of-view (FoV) from 90° to 110°. In contrast, the field of view of human vision has been reported to generally have an approximately 200° horizontal FoV when the eyeballs and head are fixed [3]. We reported and demonstrated multiple projection systems that can project VR contents with a wide FoV of 180° and high-resolution of 12K horizontal pixels to a large cylindrical-shaped screen for public viewing [4] [5] [6]. We also developed a light-emitting display system with a wide FoV using five thin-curved 4K OLED panels and demonstrated high-resolution VR contents of 10K [7]. Furthermore, we confirmed the outstanding effect of these demo systems, which have provided viewers with a feeling of immersiveness and realness.

Some wide-FoV HMDs have been reported and commercialized, such as in [8] and [9]. The headset in [8] has two slanted and horizontally long 4K panels. The eyepiece was set on the face of the panel. The main focal point was assumed to be set in the front direction. Thus, the system has a subject in which the FoV of the focused image is limited to less than 200°. The [9] with double focal lens has the feature of expanding the FoV to 140° using a general smartphone display panel.

In this study, we investigated and prototyped the optical system of a wide-FoV HMD, which was displayed with optical coupling from multiple panels aligned horizontally, and eyepieces. The system has four sets of panels and eyepieces, and it also has the feature that the central view is displayed on the central panel, whereas the peripheral view is displayed on the side panel. It can obtain a horizontal FoV of 180° with a head-tracking function.

2 OPTICAL SYSYTEM OF WIDE-FOV HMD

2.1 Requirements

The requirements for a wide-FoV HMD were set as follows:

I. The HMD can be observed in a wide viewing where the horizontal FoV is greater than 180°, corresponding to a cover range of human vision characteristics when the viewer's head movement is fixed.
II. The alignment of the HMD panels is compatible with general HMDs, and the view should be clearly focused on the viewpoint of optical construction.
III. The HMD playback system can display a high-resolution VR movie with a frame rate of 29.97 Hz or more.
IV. The images for the HMD are rendered according to the direction of head movement.

2.2 Investigating constitution of wide-FoV HMD

The constitution of the wide-FoV HMD was investigated. **Table 1** summarizes a comparison of some wide-viewing methods for HMDs.

Table 1 Comparison of wide-view methods for HMD

Method	Slanted and aligned long panel [8]	Wide and long panel with the lens combined two focal length elements [9]	Multiple (Four) panels and lenses (proposed)
FoV Range (horizontal, degree)	200	140 (not sufficient)	180–200
Optical resolution on whole view	Fair (cannot cover)	Good	Excellent
Compatibility of central view with current HMD	Fair	Good (need to change view FoV)	Excellent
Simple composition, cost	Good	Excellent	Good
Connectivity with central and peripheral views	Excellent (but focal point was not covered at whole view)	Good (different resolution)	Good (it would covered by head tracking)
Panel (number, shape, for use)	2, long, smartphone	1, long, smartphone	4, square, HMD

From a comparison of these methods, we selected a method using multiple display panels and lenses for a wide-FoV HMD.

3 OPTICAL DESIGN AND SIMULATION

3.1 Proposal of wide-FoV optical system employing four set of display panels and eyepieces

We propose an optical coupling method on the retina using four sets of display panels and eyepieces for a wide-FoV HMD. **Figure 1** shows a schematic of the optical systems of a wide-FoV HMD.

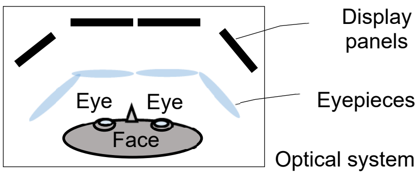


Fig. 1 Schematic of optical systems for wide-FoV HMD (upper view)

3.2 Optical design and simulation

First, we modelled a simple optical system that viewed a near display from a human eye. **Fig. 2** shows the viewing optical model, including a display panel, an eyepiece, and a human eyeball. The optical system was designed and simulated using the optical design and analysis software OpticStudio by Zemax, LLC, based on geometric optics. **Table 2** lists the parameters of the optical simulation model of an eyeball and a lens. The eyepiece was designed for a prototype using a practical material. The light source from the squared display panel was also applied to a practical size. We performed a simulation of the detected image on a retina in the eyeball by ray tracing of RGB lights from the display image while designing the parameters of the eyepiece.

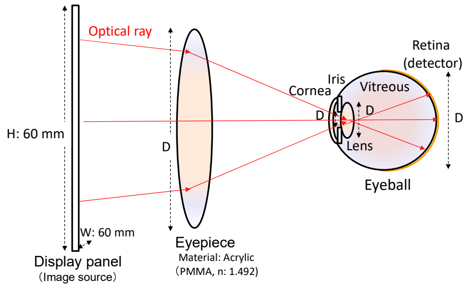


Fig. 2 Viewing optical model for HMD

Table 2 Parameters of eye model and lens

Cornea	R7.8, t0.5	n: 1.363
Iris	R6.7, t0.5, D3.6	n: 1.321
Lens	R10, t3.7, D12	n: 1.401
Vitreous	D22	n: 1.321
Retina	R11, D22	-
Eyepiece	Acrylic	n: 1.492

R: curvature radius (mm), t: thickness (mm), D: diameter (mm), and n: refractive index.

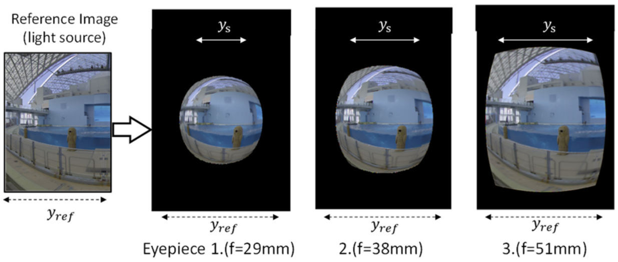


Fig. 3 Simulation results of image on HMD (Ray tracing)

Figure 3 shows the optical simulation results of the image obtained by ray tracing on the HMD. The eyepiece was designed by changing the parameters of the focal length and diameter. We evaluated the view image, particularly the distortion aberration. The maximum distortion ratio Dis was defined by the following equation. The parameter Dis was set when the lens was designed to obtain the maximum value of the modulation transfer function (MTF) for retina detection as follows:

$$Dis = \left|\frac{y_s - y_{ref}}{y_{ref}}\right| \times 100, \qquad (1).$$

where y_s denotes the size of the projection and y_{ref} the size of the reference image. **Figure 4** shows the characteristics of the maximum distortion ratio vs. the focal length of the eyepiece. The focal length was evaluated and selected when the Dis was as small as possible and practically small. As shown in **Fig. 4**, considering the small distortion and practical short focal length, we selected a focal length of 51 mm. We then applied the designed eyepiece for the prototype.

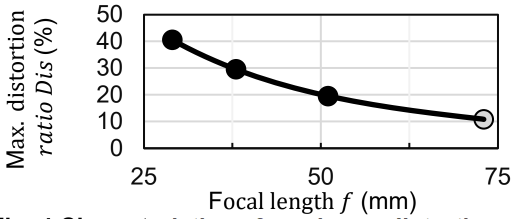
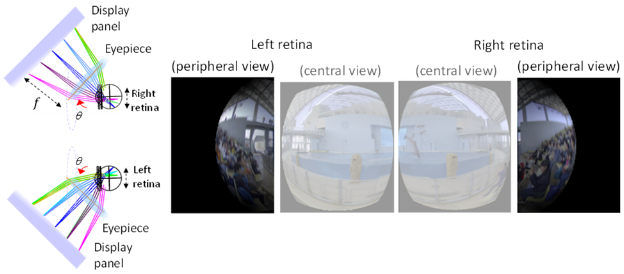


Fig. 4 Characteristics of maximum distortion ratio depend on a focal length of eyepiece

Next, we simulated image detection on the retina from the display of the peripheral view field. **Figure 5** shows the simulation results of image ray tracing on the retina from the display of the peripheral view field that has a horizontal tilt angle θ. The results demonstrate the condition with the θ = 45°. The peripheral image source was applied to the neighboring image of the central view field.



(a) Model (b) Rendered images (simulation)

Fig. 5 Results of image ray tracing on retina from the display of peripheral field (θ: 45°)

As shown in **Fig. 5**, the image of the peripheral visual field was traced to a neighboring image of the central visual field on the retina.

4 EXPERIMENTS AND RESULTS

4.1 Prototype of experimental setup

Based on the simulation results, we prototyped the experimental optical system of a wide-FoV HMD. **Figure 6** shows a schematic of the optical system.

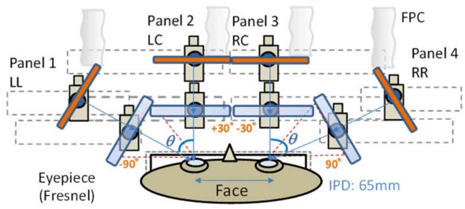
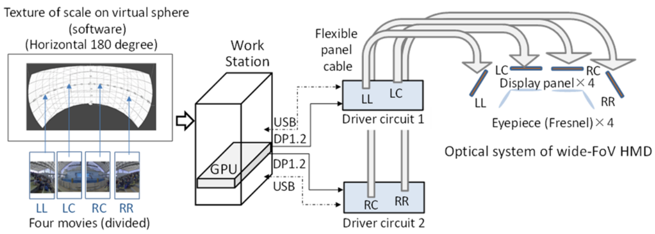


Fig. 6 Schematic of an experimental optical system of wide-FoV HMD

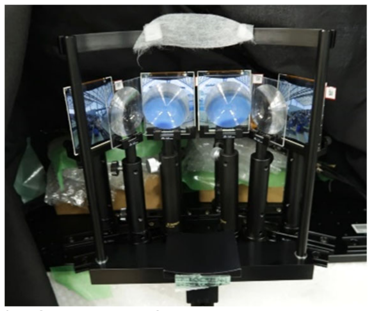
Table 3 lists the specifications of the experimental setup of the wide-FoV HMD. **Figure 7** shows the experimental setup of the wide-FoV HMD optical system. **Figure 7(a)** shows the block diagram of the system, whereas **Fig. 7(b)** shows an overview of the optical system setup.

Table 3 Specification of experimental setup of wide-FoV HMD

Display panel	Number, Type	4, LCD
	Pixels	H5760 × V1600
	Size (inch), Density (ppi)	3.5 6
Eyepiece	Number	4
	Type, Material, Pitch (mm)	Fresnel, Acrylic (PMMA), 0.25
Driver	Number	2
Interface	Image, Control	DP1.2 × 2, USB × 2
WS	GPU	NVIDIA / RTX 3090
Software	Renderer	Unity (developed)
Image sources (Movie)	Texture	Scale (evaluation)
	Number, Pixels, Frame rate (Hz)	4, H12000 × V4000, 29.97



(a) Block diagram



(b) Overview of optical system setup

Fig. 7 Appearance of an experimental setup of wide-FoV HMD optical system

4.2 Experiments and results

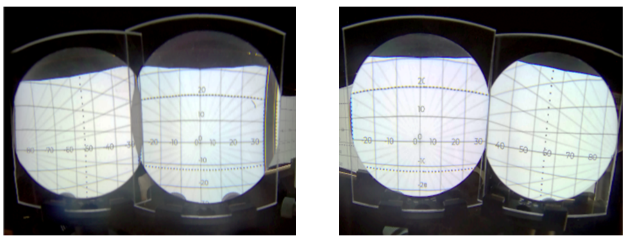


Fig. 8 Experimental results of FoV on an optical system of the wide-FoV HMD (FoV = 180°)

We conducted an experiment to evaluate the FoV characteristics of the four displays on an optical system of a wide-FoV HMD. The image source of a scale lined at 10° intervals was displayed on the panels through the experimental systems, as shown in **Fig. 7(a)**. The FoV of the central view of the left side and that of the right side were each assigned from -30° to 30° with binocular vision, and the FoV of the peripheral view of the left and right sides were each assigned from -90° to -30° and from 30° to 90°. **Figure 8** shows the experimental results for the FoV on an optical system. The photograph was captured by an omnidirectional camera of QooCAM 8K by Kandao Technology Co. Ltd with fisheye lenses. As shown in **Fig. 8**, a horizontal FoV of 180° could be obtained. Binocular vision was also confirmed normally by visual inspection.

4.3 Demonstration

We demonstrated high-resolution and omnidirectional images of an optical system of the HMD. **Figure 9** shows a snapshot of the demonstration with the playback movie (with a frame rate of 29.97 Hz) on the optical system. As shown in **Fig. 9**, binocular images of both the left and right central views were compatible with the current HMD and could watch the clearly focused vision in the entire panel area. Each side of the peripheral view was naturally aligned on the side of the central view; thus, the peripheral view indicated the expansion of the view angle with a clearly focused vision. As a result of an observation of the demonstration, we confirmed that the proposed method was effective for the optical system of the wide-FoV HMD.

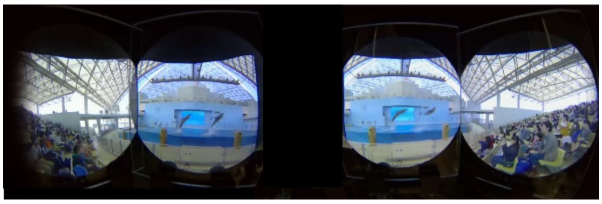


Fig. 9 Demonstration of omnidirectional images on an optical system of the wide-FoV HMD

4.4 Rendering according to head movement

We also implemented a function of rendering images according to head movement. Images for four displays are rendered from an equirectangular projection image corresponding to the acceleration and angular velocity signals from the sensor of the commercialized HMD by Oculus Quest. Its performance was confirmed. This could indicate the realization of basic performance for rendering according to head movement. The sensor of HMD will be replaced with an inertial measurement sensor device.

4.5 Discussions and subjects

Through design, simulations, and experiments, we discussed the technical features and subjects of the proposed HMD, and list the following:

(1) Features

- The appearance was optically clear on the horizontal wide-whole view and almost covered the horizontal view.
- Securing a compatibility with central view like a general HMD, a peripheral view is added on the visual perception.

(2) Subjects

- Covering vertical FoV. This system has a vertical FoV of 60°. The human vision has an angle of approximately 125°. A wide vertical FoV is also required for natural vision and immersive feeling.
- Natural connectivity of the central and peripheral views. Because the eyepieces converged each panel, the connection area was narrow in the vertical area. However, the subject would be solved by rendering function according to the head movement because the viewer could follow a remarkable object on a central view area quickly when the viewer finds the object in a peripheral view area.

5 CONCLUSIONS

We developed an optical system for a wide-FoV HMD using an optical coupling method on the retina using four display panels and eyepieces. The system was effective for wide viewing through optical simulations and experiments. In future, we will develop a compact HMD prototype that can be mounted on the head by applying an optical system and test the effect for viewers. Further, we will develop playback systems for the HMD and apply ultrahigh-resolution VR image sources to the HMD for future immersive broadcast media.

REFERENCES

[1] https://www.soumu.go.jp/menu_seisaku/ictseisaku/housou_suishin/4k8k_suishin.html.

[2] Oculus Rift (2016), https://www.oculus.com/rift/.

[3] T. Hatada, H. Sakata, H. Kusaka, “Psychophysical Analysis of the “Sensation of Reality” Induced by a Visual Wide-Field Display,” SMPTE j, 89, 560-569 (Aug. 1980).

[4] K. Mitani, KeynoteAddress-1, Proc. IDW’20 (2020).

[5] Exhibition of NHK STRL Open House 2019, https://www.nhk.or.jp/strl/open2019/tenji/e2_e.html.

[6] D. Koide, H. Kawakita, K. Yoshino, K. Ono, K. Hisatomi, “Development of High-Resolution Virtual Reality System by Projecting to Large Cylindrical Screen,” IEEE International Conference on Consumer Electronics (ICCE), 1.16 AVS (4) (2020).

[7] K. Hara, D. Koide, K. Hisatomi, T. Mishina, ‘High-resolution Cylindrical Display system for VR contents,’ ITE 70th Anniversary, Conv, 22D-1 (2020) [in Japanese].

[8] Pimax, Vision 8K (2020). https://pimax.com/ja/product/vision-8k-x/

[9] Ultra-Wide-Angle VR Headset (2020), https://www.nttdocomo.co.jp/english/info/media_center/pr/2020/1109_00.html, NTT DoCoMo.