Binocular Near Eye DFD Display System with Reduced Visual Fatigue

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ABSTRACT

Binocular near eye DFD display system was constructed using binary focus lenses and polarization modulators. Visual fatigue due to 3D image was evaluated about this DFD system and one with only vergence. It was confirmed that this DFD system 3D image has less visual fatigue than one with only vergence.

1 Introduction

Most commercial 3D head-mounted displays (HMDs) are known to cause visual fatigue for long time use. This visual fatigue is recognized to be related to the vergence and accommodation conflicts (VAC) [1].

Many approaches have been proposed to eliminate VAC, such as light field, computer hologram and varifocal optical systems [2-4]. However, these methods have the problem of requiring a high-resolution and high-speed operation display system or complicated mechanisms.

On the other hand, as a method of eliminating VAC, a method called depth-fused 3D (DFD) is known [5, 6]. DFD is a method in which the accommodation matches a 3D image that is located at a position different from the actual display image due to the visual illusion.

In this study, we proposed a binocular near eye DFD display system that matches vergence and accommodation. The two images for the DFD display image were generated by synchronizing the LCD display with the binary lens and the polarization modulator (PM) and switching by time division. We carried out flicker tests to confirm the effect of reducing visual fatigue of this DFD display system 3D image, and found that the 3D images of this DFD display system have less visual fatigue than 3D images with VAC, such as commercial HMDs.

2 The optical system configuration

Fig. 1 shows the optical system of binocular DFD display system. The optical system consists of LCDs, PMs, binary focus lenses and eyepieces using Fresnel lens. Fig. 2 describes the operation of the optical system. Fig. 2 (a) shows PM OFF state and (b) shows PM ON state. In the actual binocular DFD display system, there are two optical systems, but in Fig. 2, the optical system for one eye is described.

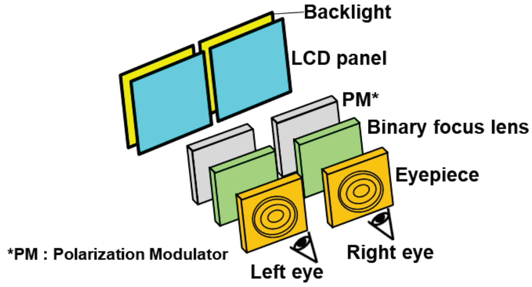
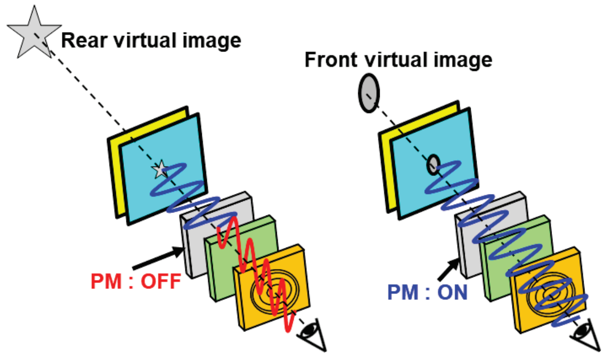


Fig. 1 Schematic diagram of the optical system



(a) PM OFF (b) PM ON

Fig. 2 The operation of the optical system

The light emitted from the LCD is switched the two polarization directions by PM. A binary focus lens is a lens whose focal distance f changes according to the polarization direction of the incident light. [7]

A virtual image of the LCD is displayed at different distances depending on the combined focal distance of the binary focus lens and the eyepiece for each of the two types of PM emission light.

By switching this operation with high-speed time division, the observer can recognize that both the front and rear virtual images are displayed, and by changing the brightness ratio of these virtual images, the DFD image becomes possible.

When the two virtual image distances were measured, it is as shown in Table 1, and they show good agreement.

Table. 1 Design and measurement value of virtual image distance

Virtual image	Design value (mm)	Measurement value (mm)	
		Left eye	Right eye
Front	741	735	730
Rear	1219	1239	1212

3 Virtual image layout and brightness

The method of setting the vergence angle of the virtual images and the brightness for the DFD display are described below.

Figure 3 shows an example of displaying front and rear virtual images based on the position of the 3D image (A). The 3D image due to the vergence of the front virtual images pop out in the rear direction, and the 3D image due to the vergence of the rear virtual images pop out in the front direction. Both virtual images' vergence angle match the vergence angle θ1 and θ2 of the 3D image (A) in Fig. 3.

The brightness ratio of the front and rear virtual images is determined by the ratio of the distance between the 3D image (A) and each virtual image L1 and L2 in Fig. 3.

The 3D image (A) brightness is determined by the sum of the brightness of the front virtual image and the rear one.

The above 3D image generation method is described as **"DFD + vergence"** in the text of this study.

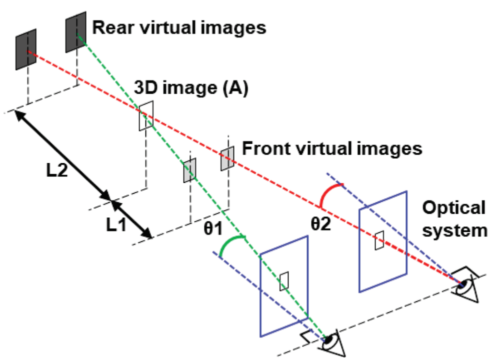


Fig. 3 Virtual image layout

4 Signal processing system configuration

In order to realize DFD display image with front and rear virtual images, we examined a display method to switch between front and rear virtual image with high-speed time division.

Figure 4 shows a block diagram of the signal processing system. The four images from A to D in Fig. 4 needed to generate the binocular DFD 3D image are generated on PC. The image data is stored as a set for the right eye and the left eye. The image data is transmitted to the signal processing board as a DP signal.

The signal processing board stores the LCD display image data and sends these image data alternately to the LCD frame by frame for front and rear virtual images.

The signal processing board also generates PM and backlight drive signals that are synchronized with the operation of the LCD.

In order to prevent crosstalk from occurring in the front and rear virtual images, the GtoG response speed of the LCD was taken into consideration for the drive timing and backlight blinking was adopted.

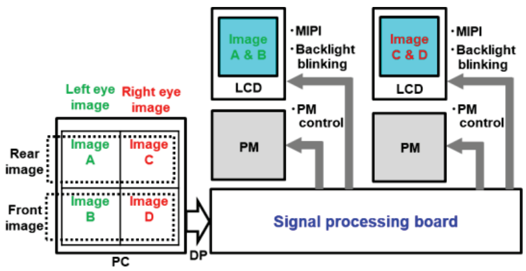


Fig. 4 Schematic diagram of Signal processing

5 Evaluation of visual fatigue

We checked whether there is a difference in visual fatigue between the 3D image by DFD + vergence and the 3D image with only one virtual image position like commercial HMDs currently.

The flicker test [9] was used as a confirmation method. The flicker test is known as one of the means for assessing visual fatigue and has been widely used in the fields of ergonomics and occupational health. In the test, the subject observes the blinking light. The blinking frequency is changed, and the frequency of the threshold value (Critical Fusion Frequency: CFF) in which the blinking is recognized as continuous lighting is measured. A decrease in the CFF value is considered to represent a depression in the visual system function.

5.1 Subjects and Flicker test device

Five adults (4 males and 1 females) participated in the experiment. We got informed consent from all subject before the experiment.

T.K.C.501c (Takei Scientific Instruments Co., Ltd) was used for the flicker test.

5.2 Experimental protocol

Fig. 5 shows the experimental protocol. All subjects performed the task of continuing to view the 3D displayed stimulus. Subjects were measured CFF at each flicker test timing before (timing A), after (timing D), and every 5 minutes (timing B and C) of the task. Each subject perform 4 flicker tests at each flicker test timing.

The average value of the three values excluding the maximum and minimum values was defined as the CFF value of each subject at each timing.

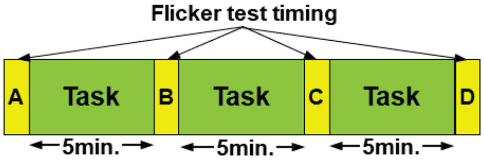


Fig. 5 Experimental protocol

5.3 Stimulus

The stimulus used for experiment is shown in Fig. 6. The letters of the alphabet are displayed in white and the background is displayed in black. The stimulus was displayed so that the viewing angle from the subject was constant at 2 ° regardless of the display distance. The stimulus was presented at the center of the subject's eyes.

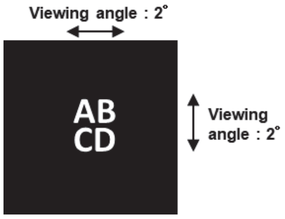


Fig. 6 Stimulus

5.4 Evaluated display method and 3D image distance

We have prepared the following three display methods of 3D image using our newly developed display system.

(1) Use only front virtual image with vergence
(Virtual image distance: 741 mm)

(2) Use only rear virtual image with vergence
(Virtual image distance: 1219 mm)

(3) Use DFD + Vergence

The 3D image distances used for the experiment were 741, 880, 980, 1080, and 1219 mm. Table 2 shows the combination of the experimental display methods and 3D image distances. For 741 and 1219 mm 3D images, only the display in which where the vergence angle matched accommodation was performed. For 880, 980, and 1080 mm 3D images, all three types display methods were performed.

Table. 2 The combination the display methods and 3D image distances

3D image distance (mm)		741	880	980	1080	1219
Display method	only front	○	○	○	○	–
	only rear	–	○	○	○	○
	DFD + vergence	–	○	○	○	–

6 Evaluation results and discussion

Fig. 7 shows the flicker value ratio during the experiment when 3D image is displayed at the distances of 741 mm and 1219 mm with vergence and accommodation matched, and when it is displayed at the distance of 980 mm with the DFD + vergence. The flicker value ratio is a value normalized by the CFF value of the flicker test A in Fig. 5 before starting the task as shown in the following equation (1).

$$\text{Flicker value ratio} = \frac{\text{CFF of any of flicker tests A to D}}{\text{CFF of A}} \times 100\ (\%) \quad \dots (1)$$

Each plotted value in figure is the average of the 5 subjects Flicker value ratio. The error bar in the graph shows the maximum and minimum values. When the t-test ($p < 0.05$) was used to determine whether there was a significant difference between each value every 5 minutes, no significant difference was found. We also made the above comparison for 3D image with DFD + vergence at distances of 880 mm and 1080 mm, and confirmed that there was no significant difference in either case. From this result, it can be expected that the observation of 3D image generated by DFD + vergence is the same degree of visual fatigue as the 3D image in which vergence and accommodation are matched.

3D image distance (mm)		741	880	980	1080	1219
Display method	only front	○	○	○	○	–
	only rear	–	○	○	○	○
	DFD + vergence	–	○	○	○	–

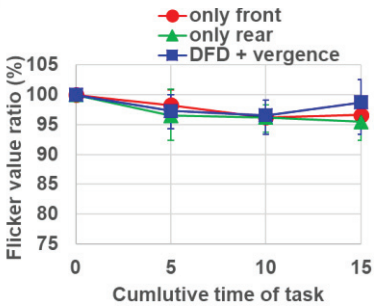


Fig. 7 The comparison result between vergence and accommodation matching image and DFD + vergence image

Fig. 8 shows the flicker value ratio when a 3D image with 880 mm distance is displayed with only one virtual image of either 741 mm or 1219 mm at vergence angle corresponding to a distance of 880 mm, and when is displayed using DFD + vergence.

When it was judged by the t-test ($p < 0.05$) whether there was a significant difference between each value every 5 minutes, the significant difference was confirmed in 10 minutes or more between the case of DFD + vergence and the case of one virtual image.

Fig. 9 shows the flicker value ratio when a 3D image with 980 mm distance is displayed with only one virtual image of either 741 mm or 1219 mm at vergence angle corresponding to a distance of 880 mm, and when is displayed using DFD + vergence. And Fig. 10 shows the same experiment result tin the case of the 3D image distance is 1080mm. When the display distance of the 3D image is 980mm in Fig. 9, there was a significant difference in 15 minutes between the case of DFD + vergence and the case of a single virtual image. And when the display distance of the 3D image is 1080mm in Fig. 10, there was a significant difference in 10 minutes or more between the case of DFD + vergence and the case of a single virtual image.

From these results, it can be expected that the 3D image generated by DFD + vergence has less visual fatigue than the image generated only vergence.

3D image distance (mm)		741	880	980	1080	1219
Display method	only front	○	○	○	○	—
	only rear	—	○	○	○	○
	DFD + vergence	—	○	○	○	—

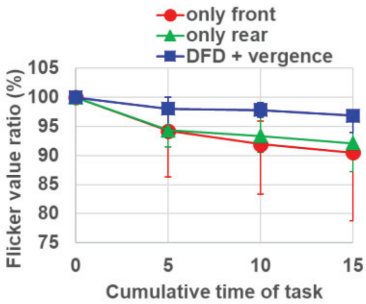


Fig. 8 Comparison result of 3D images between one distance virtual image and DFD + vergence image (3D image distance: 880 mm)

3D image distance (mm)		741	880	980	1080	1219
Display method	only front	○	○	○	○	—
	only rear	—	○	○	○	○
	DFD + vergence	—	○	○	○	—

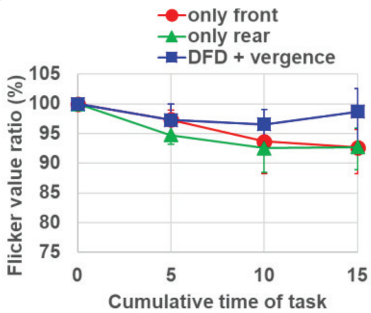


Fig. 9 Comparison result of 3D image between one distance virtual image and DFD + vergence image (3D image distance: 980 mm)

3D image distance (mm)		741	880	980	1080	1219
Display method	only front	○	○	○	○	—
	only rear	—	○	○	○	○
	DFD + vergence	—	○	○	○	—

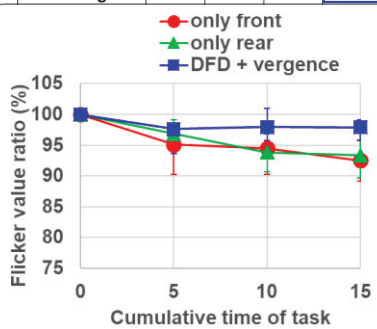


Fig. 10 Comparison result of 3D image between one distance virtual image and DFD + vergence image (3D image distance: 1080 mm)

7 Conclusion

We constructed a binocular DFD display system using binary focus lenses and PMs. Two virtual images at a distance of 741 mm and 1219 mm are displayed in high-speed time division and it seemed to be displayed to the observer simultaneously. And DFD image was performed using these images.

Furthermore, using the above display system, the DFD + vergence 3D image and the vergence-only 3D image were displayed at the same distance, and the visual fatigue caused by each 3D image was compared by a flicker test.

As a result of the experiment, we judge that the 3D image by DFD + vergence display system has the potential to greatly reduce visual fatigue compared to 3D images with only one virtual image position such as HMD on the market.

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