Image Quality Improvement of Glasses-Free 3D Display Using Parallax Barrier with Eye Tracking System to Expand Viewing Zone in All Directions

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Keywords: glasses-free, stereoscopic, eye-tracking

ABSTRACT

When we expand the viewing zone of glasses-free 3D display, it is effective to divide screen into multiple areas, and control them optimally. While, lines that cause uncomfortable viewing occur on all boundaries of the divided areas. We propose to make the lines invisible by the image processing.

1 INTRODUCTION

The 3D display has been expected to have a large market, but is not yet popular. The conditions required to them for its widespread use are glasses-free, high image quality, wide viewing zone and so on. While there are various glasses-free 3D display methods, the stereoscopic display using a parallax barrier satisfies the two conditions of the former, but it has a drawback that the viewing zone is limited.

We have developed the 3D display system using a parallax barrier with eye-tracking system, which has high resolution and needs viewers wearing no special glasses [1]. In addition, by dividing the screen into multiple areas according to the detected viewing position and controlling these areas optimally, it was possible to obtain the stereoscopic vision even when the viewer moved in the depth direction [2]. As a result, the viewing zone could be dramatically expanded. However, if the screen is divided into multiple areas and each area is controlled individually, lines resulting from the change in the control state appear at the boundaries of the divided areas, which makes stereoscopic viewing uncomfortable. These lines, which we define as the control boundary lines, increases in number as the viewing distance moves away from the Optimal Viewing Distance (OVD). Also, it is a major factor causes uncomfortable stereoscopic vision.

In this paper, we propose a method to erase the control boundary lines by changing the image arrangement of the binocular parallax image smoothly across the divided areas. In this method, we firstly define switch sub-pixels as the sub-pixels that cause a difference in the image arrangement of the binocular parallax images between the adjacent divided areas. The mixed sub-pixel value of the left-eye image and the right-eye image are displayed on the switch sub-pixels, and the mixing ratios are changed according to the positions of the switch sub-pixels in the divided area.

As a result, the binocular parallax image can smoothly switch between each divided area and this method makes the control boundary line invisible. In order to verify the effectiveness of this proposed method, we measure crosstalk at certain viewing distances and we perform subjective evaluation.

2 METHOD FOR IMPROVING IMAGE QUALITY

2.1 Concept of Expanding the Viewing Zone

Fig. 1 shows the image arrangement of the binocular parallax image on the display observed with the right eye. Gray parts in the figure shows the parallax barrier, and its apertures are slanted to prevent moire, and its slant angle is θ (= $\tan^{-1}(1/6)$). We compose a binocular parallax image with consecutive *n* sub-pixels, and assign sub-pixel numbers in *n* cycles. The sequence of *n* depends on the *θ* and determines the barrier pitch. Then, the stereoscopic vision is realized by displaying the right-eye image (red parts in Fig. 1) in sub-pixel numbers #8 to #14 and the left-eye image (blue parts in Fig. 1) in #1 to #7. By adopting the slanted barrier and displaying the single-eye image on consecutive sub-pixels, the freedom in design is improved and we can reduce crosstalk.

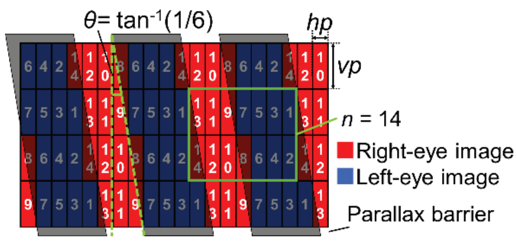


Fig. 1 Concept of binocular image arrangement.

As shown in Fig. 2, the dot spaces are formed at OVD by placing a parallax barrier in front of the display. These dot spaces are formed corresponding to the consecutive *n* sub-pixel numbers on the display and are used as the standard to understand the viewed conditions of the sub-pixels through the parallax barrier. The width of a dot space *f* is given by

$$f = \frac{2\mathrm{E}}{n}, \tag{1}$$

where E is the interocular distance.

When the viewer moves in the horizontal direction at the OVD, it is possible to keep stereoscopic vision by changing the image arrangement pattern of the binocular parallax image with the dot spaces as standards.

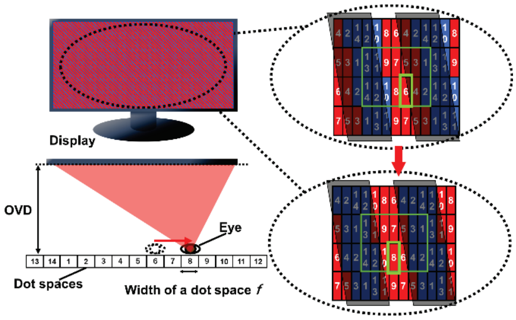


Fig. 2 Expansion of viewing zone in the horizontal direction.

Even if the viewer moves in the depth direction, the viewing zone can be expanded by grasping the light ray from the sub-pixel using the dot spaces as standards. As shown in Fig. 3, when the viewer moves in the depth direction, the screen is divided into multiple areas by the lines connecting the edges of the dot spaces on the OVD and the position of the viewer's eye. In addition, the image processing is performed in each divided area, where the center of the binocular image arrangement at each aperture of the parallax barrier is controlled to match the dot space number. However, because each divided area has slightly different image arrangement, the control boundary lines occur at the boundaries of each divided area. Then, the width of divided areas *s* on the screen is given by

$$s = f \times \frac{\mathrm{OVD}}{|\mathrm{OVD} - z|} = \frac{2\mathrm{E}}{n}\frac{\mathrm{OVD}}{|\mathrm{OVD} - z|}. \tag{2}$$

2.2 Control to Erase Control Boundary Lines

Fig. 4 shows the boundaries of the divided areas of the screen. On the left side of the boundary, the right-eye image is composed of sub-pixels whose numbers are #6 to #12, and on the right side, these are #5 to #11. When the right eye observes those sub-pixels, the control boundary line is observed due to the transition of the observed sub-pixels, that is, the transition of the display of the switch sub-pixels, #5 and #12 sub-pixels in the figure. When we use the position of the right eye as the control reference for dividing the screen, it is expected that control boundary lines will be almost invisible in the viewing state for the right eye. This is because, considering the aperture pitch of the parallax barrier, as shown in Fig. 4(a), most of the switch sub-pixels are hidden behind the barrier. On the other hand, it is expected that control boundary lines will be more conspicuous in the viewing state for the left eye. This is because the difference between the ideal control state for the right eye and the ideal control state for the left eye increases the visible area of the switch subpixels in the viewing state for the left eye. When we use the left eye as the control reference, results of each viewing state is the opposite.

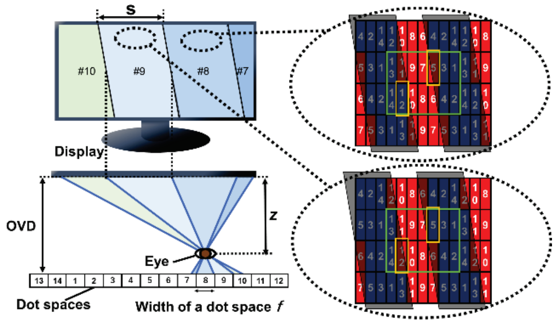
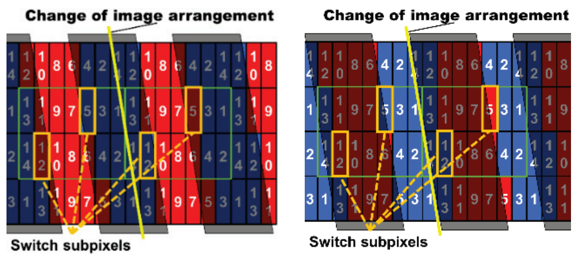


Fig. 3 Expansion of viewing zone in the depth direction.



(a) Right eye view (b) Left eye view

Fig. 4 Change of image arrangement.

In this paper, we propose the method to erase the control boundary lines by displaying the mixed images of the right-eye image and the left-eye image on the switch sub-pixels to make the transition at the boundary smooth. The sub-pixel value of the switch sub-pixel $PV_s(x,y)$ is given by

$$PV_s(x,y) = \frac{W - h(x,y)}{W} \cdot PV_R(x,y) + \frac{h(x,y)}{W} \cdot PV_I(x,y)\,, \tag{3}$$

according to the coordinate (x,y) of the switch sub-pixel on the screen. Then, $PV_R(x,y)$ is the sub-pixel value at coordinate (x,y) in the image arrangement in the divided area that includes coordinate (x,y), and $PV_I(x,y)$ is the sub-pixel value of the crosstalk image at coordinate (x,y). $h(x,y)$ is the horizontal distance from the coordinate (x,y) to the the nearest edge of processing area, and *W* is the width of the processing area centered on the control boundary, and the range is 0 to *s*. Then, if $PV_R(x, y)$ is from the right-eye image, $PV_l(x, y)$ will be from the left-eye image, conversely, if $PV_R(x, y)$ is from the left-eye image, $PV_l(x, y)$ will be from the right-eye image. Thus, in the proposed method shown in Fig. 5, the mixture ratio on the switch sub-pixels is determined by the coordinates of the sub-pixels in the divided area. Then, if *W* is increased, the display of the mixed images is increased, so that an increase in crosstalk is expected, and if *W* is decreased, the change in image arrangement becomes abrupt and uncomfortable viewing is expected.

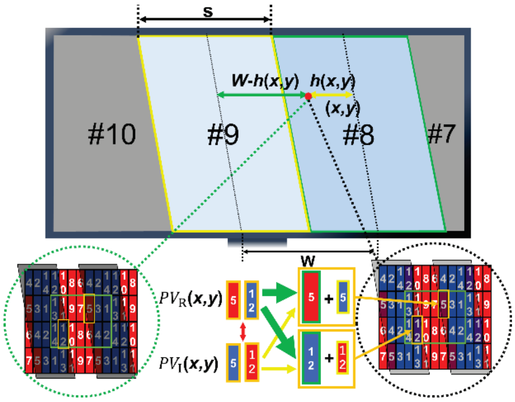


Fig. 5 The determination of the sub-pixel value of the switch sub-pixel.

As a result, the sub-pixel value of the switch sub-pixels change smoothly across the boundary line. Along with this, the image arrangement changes smoothly across the boundary line, so the control boundary lines can be erased. Fig. 6 shows the image arrangement of the proposed method. The purple parts of the image arrangement represent mixed images.

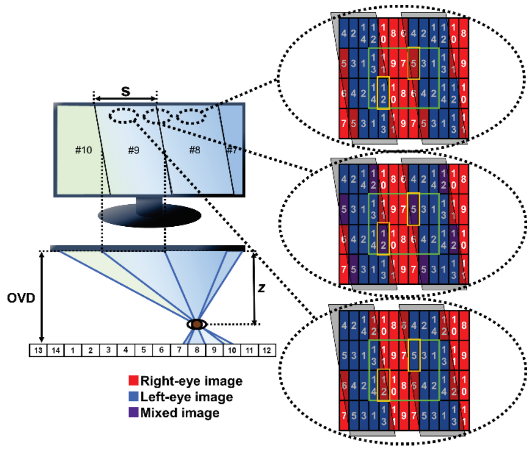


Fig. 6 Image arrangement of the proposed method.

3 EVALUATION OF THE PROPOSED METHOD

In order to confirm the effectiveness of the proposed method, we made a prototype system with the specifications shown in Table 1 using a Full-HD display and a parallax barrier. We used the position of the right eye as the control reference for this prototype system. To evaluate the proposed system, we measured the average crosstalk ratio (CTR) of the screen and subjectively evaluated the captured images.

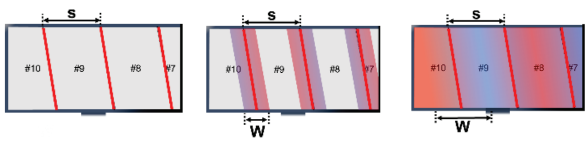
Table 1 Specifications of prototype system

Display resolution	1920 x 1080
Sub-pixel pitch (H)	0.09225 mm (Portrait)
Barrier pitch (H)	0.64256 mm
Barrier aperture ratio	35.7 %
Aperture slant angle	$\tan^{-1}(1/6)$
OVD	516 mm

To evaluate the crosstalk ratio and the image quality, we displayed the black, the white, the black-and-white images and the red-and-blue images and captured the viewing images at the viewing distance 566 mm and 616 mm by a camera. The distance between the right-eye viewing position and the left-eye viewing position was the interocular distance E in the horizontal direction. Here, the white image is a uniformly white image, the black image is a uniformly black image. The black-and-white image is a composite image that consists of a uniform black image for the right-eye image and a uniform white image for the left-eye image. Similarly, the red-and-blue image is a composite image that consists of a uniform red image for the right-eye image and a uniform blue image for the left-eye image. As shown in Fig. 7, for black-and-white images and red-and-blue images, we performed the processing of the proposed method within the width of processing *W* centered on the control boundary lines. The *W* values for the three images A, B, and C were *W* = 0, *s* / 2, and *s*, respectively. Here, A is a conventional image that has not been subjected to the proposed method, B is an image that has been subjected to the proposed method in half the entire screen, and C is the image that has been applied to the entire display.

Here, the red line in the figure represents the control boundary line, and the colored part represents the range to which the proposed method is applied. The average pixel values PV_w, PV_b and PV_c of the entire screen were acquired from each of the white, black, and black-and-white images, and CTR of the screen was given by

$$CTR = \left(\frac{PV_c - PV_b}{PV_w - PV_b}\right) \times 100[\%]\,. \tag{4}$$



(a) A (*W* = 0). (b) B (*W* = *s*/2). (c) C (*W* = *s*).

Fig. 7 Processing range of each display image.

Table 2 shows CTR of images A, B and C. It can be seen from Table 2 that the CTR does not increase even if the processing range of the proposed method is expanded. And also, the crosstalk ratio of the right eye is lower than that one of the left eye at each viewing distances and display images. This is because the prototype system is designed to reduce the right-eye crosstalk.

Table 2 Relationship between image and CTR.

	z = 566 mm		*z* = 616 mm	
	Right-eye CTR.	Left-eye CTR.	Right-eye CTR.	Left-eye CTR.
A.	5.84%	7.83%	3.98 %	13.04 %
B.	5.23%	7.15%	3.51 %	11.83 %
C.	4.63%	6.05%	3.26 %	10.69 %

Next, the captured images of the red-and-blue images are shown in Figs. 8 and 9. As seen in the figures, the control boundary lines seen in image A are erased in the order of images B and C at each viewing distance.

(a)

(b)

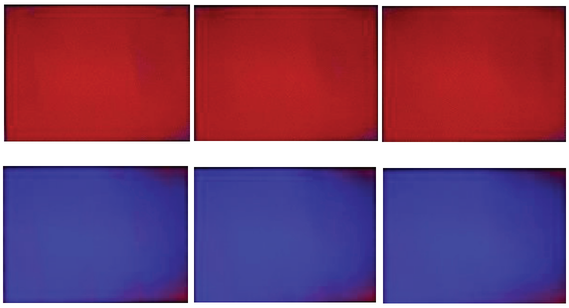


Image A. Image B. Image C.

Fig. 8 (a) Right-eye captured image and (b) Left-eye captured image (*z* = 566mm).

(a)

(b)

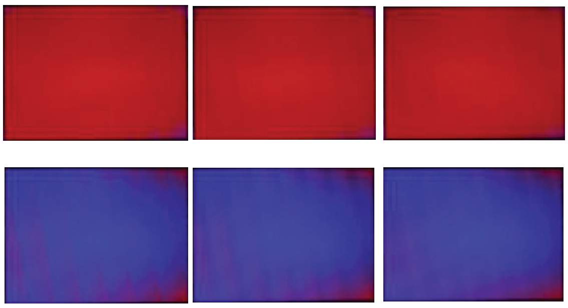


Image A. Image B. Image C.

Fig. 9 (a) Right-eye captured image and (b) Left-eye captured image (*z* = 616mm).

4 DISCUSSION

The effect of the display of mixed images on the switch sub-pixels on the crosstalk ratios is found in Table 2, where the crosstalk ratios with and without processing show little change. Furthermore, it is generally considered that a comfortable stereoscopic vision can be obtained when the crosstalk ratio is less than 10%, and the measured values generally satisfy that condition. Further, from the subjective evaluation of Figs 8 and 9, the control boundary lines are observed in image A at each viewing distance. As with the theory, the control boundary lines of the left eye are more conspicuous than control boundary lines of the right eye. Theoretically, the control boundary lines should be almost invisible from the right eye, but in reality, they are observed because of slight deviations in the design accuracy of the display and the viewing position. In addition, it can be confirmed that the number of the lines increased when the viewing distance was 616 mm which was further away from OVD than 556 mm. On the other hand, it can be confirmed that the control boundary lines are erased for images B and C that have been subjected to the proposed method at each viewing distances. When the images B and C are subjectively compared, it can be said that the control boundary line is less noticeable in the image C, therefore image C realizes more comfortable stereoscopic vision than the other images. From those results, the effectiveness of the proposed method was confirmed because the image C realizes more comfortable stereoscopic vision than the other images in the quantitative evaluation and the subjective evaluation. In addition, by applying proposed method, we plan to study how to reduce the control boundary of both eyes equally by using a virtual eye located at the center of each eye as the control reference.

5 CONCLUSIONS

We propose a method to erase the control boundary lines by displaying the mixed images of the left-eye images and the right-eyes images on the switch sub-pixels and changing the mixing ratio according to the position of the switch sub-pixels in the divided areas. Through experiments, it was confirmed that the control boundary lines were erased, and that the change in the crosstalk rate by the proposed method did not affect comfortable viewing. Compared with the conventional method, the proposed method enables more comfortable binocular stereoscopic viewing with less crosstalk in a wide range.

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