A Full-HD Super-Multiview Display Based on Adaptive Time-Division Multiplexing Parallax Barrier

Yuta Watanabe and Hideki Kakeya (member)

Abstract This paper proposes a super-multiview autostereoscopic display with a full HD resolution. A super-multiview display, where multiple views are generated around the eyes to stimulate focal accommodation, requires generation of images for many viewpoints. When we apply time-division multiplexing, the number of views can be increased without losing spatial resolutions, while flickers stand out as the number of time-division increases. To attain more views with the same refresh rate, we set two LCD panels so that they may face the opposite directions. In this way, the order of color filter is reversed and the light rays of different colors are directed to different orientations. Each color creates a different directional light to achieve three fold views. To extend the viewing zone in the depth direction, we introduce adaptive time-division, where quadruplexing is applied when the viewer is farthest, quintuplexing is applied when the viewer is in the middle, and sextuplexing is applied when the viewer is nearest. Expansion of viewing zone and the effect of focal induction are confirmed by the experiments using a prototype system based on the proposed method.

Keywords: displays, super-multiview, focal accommodation, parallax barrier, time division multiplexing, 3D.

1. Introduction

In the conventional stereoscopy, two different images with binocular parallax are shown to each eye, where binocular vergence is induced in front of or behind the screen, while focal accommodation is always adjusted to the screen. This vergence-accommodation conflict often causes eye fatigue of the viewer. Super-multiview displays have been proposed as one of the solutions to this problem.1-4

Super-multiview displays project multiple light rays to the pupil. When two or more rays are projected onto the retina, focal accommodation is induced to the stereo image so that the image on the retina may not be a double image. To realize a practical super-multiview display, a huge number of views are required to be displayed to cover a wide viewing zone.

To overcome this problem, Takaki et al. have proposed a system to generate light field only around the tracked eye positions.5 However, the resolution of the presented image decreases because it is based on spatial multiplexing using a lenticular lens.

Recently, several autostereoscopic displays that attain full resolution of the display panel have been proposed. One solution is time-division multiplexing parallax barrier,6-7, where half of the resolution of each view is shown in one frame, while the other half is shown in the other frame by shifting the phase of the barrier and the image pattern. To suppress perceived flickers, 120 Hz refresh rate is necessary to ensure that each eye sees the full resolution image at 60 Hz. In addition, head-tracking technology solves the problem of limited viewing zone.8-11 By monitoring the position of the observer, the image or the barrier pattern is adjusted accordingly to move the viewing zone so that it may always follow the position of the observer to maintain autostereoscopy.

To reduce crosstalk, Zhang et al. have proposed time-division quadruplexing parallax barrier.12-15 In this system the same image is delivered to two of the four viewpoints, which suppresses emergence of crosstalk when each of the viewer’s eyes is positioned between the two viewpoints corresponding the same image.

In this paper we propose a full-HD super-multiview display based on adaptive time-division parallax barrier and report the results of experiments to measure the focusing of human eyes to the time-multiplexing super-multiview display.
2. Related Work

One of the causes of eye fatigue peculiar to stereoscopic vision is vergence-accommodation conflict, as shown in Fig. 1. When you see things in the real world, focusing and binocular convergence are adjusted to the same depth. However, when you see a stereoscopic image with a conventional 3D display, the binocular convergence is induced to the 3D image away from the screen, while the focus is adjusted to the display screen. This discrepancy often causes eye strain of the viewer.

One of the methods to solve this problem is super-multiview display technology. As shown in Fig. 2, super-multiview displays project images for two or more viewpoints onto a single eye. Then, in order to prevent the image from being doubled, the focal point is guided to the intersection of the light rays. When the focal accommodation is properly induced, the vergence-accommodation conflict disappears.

To realize a super-multiview display, a huge number of images for continuous viewpoints have to be generated. To reduce the number of viewpoints required, Takagi et al. proposed a system that displays multiview images only around the eyes by using eye-tracking as shown in Fig. 3. Here $w$ denotes the width of the left and the right viewing zones. The width of the region between them is given by $2nw$, where $n$ is a natural number. The distance between the centers of the left and the right viewing zones is given by $2nw + w$, and this distance becomes identical to the inter-pupillary distance $P$ when

$$w = P/(2n + 1)$$

holds.

When the number of viewing zones for the left and the right eyes is denoted as $V$, the pitch of super-multiviewing zone is given by

$$v = \frac{P}{(2n + 1)V}$$

Though this method can reduce the number of required viewpoints, the resolution of the presented image is reduced due to the spatial multiplexing based on lenticular lens optics.

3. System Design

3.1 Super-multiview display with time-division multiplexing parallax barrier

The time-division parallax barrier is a technique to increase the number of viewpoints in autostereoscopic displays without spatial resolution loss\(^{16-18}\). Figure 4 shows an example of the time-division quadruplexing parallax barrier. Images for different viewpoints are displayed on pixels A, B, C and D by switching among four barrier patterns and display patterns at a high speed. When the refresh rate of the display panel is 120 Hz, 30 Hz interlace image is reproduced.

As described above, we can increase the number of viewpoints when we use a large number of time division, while the problem of flicker emerges. To attain more...
views with the same refresh rate, we set two LCD panels so that they may face the opposite directions. In this way, the order of color filter is reversed and the light rays of different colors are directed to different orientations\(^19\). Each color creates a different directional light to achieve three fold views, which generates 18 views when time-division sextuplexing is applied. Thus nine different views can be assigned to the left-eye image, while the other nine views can be delivered to the right-eye image. Figure 5 shows the principle of this system.

Nine left-eye images are shown at pixels L1-L9 and nine right-eye images are shown at pixels R1-R9. As shown in Fig. 6, the width of viewing zone for each viewpoint is determined by the distance between the observer and the display. Now, let us denote the width of one subpixel as \(p\), the distance between displays as \(d\), and the distance between the display and the observer as \(D\). Then, because of the similarity of triangle, the width of viewing zone \(v\) corresponding to each subpixel is given by

\[
v = p \frac{D}{d}.
\]

Under the conditions where \(p = 0.092\) mm, \(d = 60\) mm, and \(D = 900\) mm, the width of each viewing zone is about 1.4 mm. As shown in Fig. 7, when nine viewpoints are assigned to the left and right eyes respectively, the total width of viewing zone provided to each eye is \(1.4 \times 9 = 12.6\) [mm]. Here the center-to-center distance between the left-eye viewing zone and the right-eye viewing zone is 63 mm when \(n = 2\). Since the average distance between the eyes is about 63 mm, it is possible to present appropriate stereoscopic images to the left eye and the right eye.

The images observed with the prototype system is shown in Fig. 8. Here the left cone is shown 100 mm in front of the screen and the right cone is shown 100 mm behind the screen. When the focus of the camera is on the front cone, the cone in the back is blurred, while the front cone is blurred when the focus is on the cone in the
3.2 Expansion of viewing zone

Time-division multiplexing parallax barrier method can realize super-multiview and full-HD resolution, while the viewing zone is limited in the depth direction. Figure 9 shows the visual field around both eyes when the distance to the observer is 1125 mm in an 18-view display when \( p = 0.092 \) [mm] and \( s = 30 \) [mm]. Here the width of viewing zone for each viewpoint becomes 3.5 mm according to equation (3), which means the total width of viewing zone for each eye comprising nine views is 31.5 mm. In this case, the left-eye image and the right-eye image are not observed properly as shown in Fig. 9. To solve this problem, the width of viewing zone for each eye has to be changed adaptively.

In order to change the width of viewing zone, we propose a method to apply variable time-division parallax barriers. It is known that the viewing zone of time-division multiplexing parallax barrier changes in accordance with the number of time divisions [18], [20]. This is because the unit width of the interleaved image depends on the number of time divisions of the time division parallax barrier.

Figure 10 shows the relationship between the parallax barrier and the unit width of the interleaved image. In Fig. 10, the width of the parallax barrier comprising a slit and a barrier is indicated by a red arrow, the width of an interleaved left-eye image unit and right eye image unit are indicated by a yellow arrow and a blue arrow respectively.

As shown in Fig. 10, the width of the image for each eye is half of the parallax barrier unit. Therefore, in the time-division parallax barrier, the width of image unit comprising a pair of left-eye image and right-eye image changes in accordance with the number of time divisions.

Figure 11 is a schematic diagram showing the relationship between the number of time divisions and the viewing zone. As shown in Fig. 11, as the number of time divisions becomes smaller, the width of image unit also becomes smaller, which leads to a narrower angle of viewing zone. Here the viewing zone securing stereoscopy for a person with the same inter-pupillary distance becomes farther as the angle becomes narrower. Conversely, if the number of time divisions increases, the viewing zone securing stereoscopy comes closer. Thus a deep stereoscopic viewing zone is secured if the number of time-division is changed adaptively.
For example, let us consider the case where subpixel pitch $p$ is 0.092 mm and the interval between the LCD panels $d$ is 30 mm again. In this case, the width of each viewpoint $v$ changes depending on the distance $D$ between the display and the observer as shown in Fig. 12.

When $D = 750$ [mm], $v = 2.3$ [mm], which means that the width of viewing zone for each eye is $2.3 \times 9 = 20.7$ [mm] when time-division sextuplexing is applied. In this case, the left eye and the right eye are both located at the center of the group of viewpoints for each eye when the inter-pupillary distance is 63 mm as shown in Fig. 13.

In the same manner, $v = 2.76$ [mm] when $D = 900$ [mm] and $v = 3.45$ [mm] when $D = 1125$ [mm]. Time-division quintuplexing, which generates 15 views in total combined with use of three colors for different viewpoints, attains proper stereoscopy when $D = 900$ [mm], for the two eyes 63 mm apart from each other are located at the center of the group of viewpoints for each eye. Time division quadruplexing, comprising 12 viewers, attains proper stereoscopy when $D = 1125$ [mm] for the same reason.

Figure 14 shows the images observed with the prototype system. Here a white image is shown to the left eye and a black image is shown to the right eye. As the figure shows, proper stereoscopy is obtained by sextuplexing at $D = 750$, by quintuplexing at $D = 900$, and by quadruplexing at $D = 1125$ as expected.
4. Experiment

The main purpose of a super-multiview display is to induce focal accommodation of the observer. Here we conduct an experiment to measure the human focal accommodation with the time-division multiplexing super-multiview display explained so far\(^{21}\).

In the experiment, parallax images for 18 viewpoints were aligned in the horizontal direction by the sextuplexing time-division display. To measure the human focal accommodation response, we used an auto refractometer (WAM-5500). The distance between the two panels was 30 mm, and the distance between the panel and the observer was about 460 mm. The viewing area width per viewpoint was 1.4 mm and the viewing area width per eye was \(1.4 \times 9 = 12.6 \text{ mm}\). Super-multiview images were displayed 70 mm in front of and 100 mm behind the display screen. One eye of the observer was shielded to suppress the binocular effect.

At first, a stereoscopic image was displayed in front of the display, and after 15 seconds, it was displayed behind. Accommodation response was measured while three kinds of images (an asterisk, a thin cone, and a Landolt ring) were displayed to 6 subjects, all male in their twenties with corrected eyesight 6/9 or higher. When the Landolt ring was shown, the subjects were asked to answer the directions of opening while the ring changed after each answer. A schematic of the experiment is shown in Fig. 15.

The results for 6 subjects are shown in Figs. 16-21. In these figures, “D” is the diopter, which is supposed to be the inverse of the distance from the eye to the focused object with a negative sign. In this experiment, the diopter is supposed to be \(-2.56\) when the presented image is close (in the first 15 seconds) and \(-1.79\) when the image is far (after 15 seconds) theoretically. Note that this value varies from person to person and the change in the diopter value is more important than the value itself.

Although the response depends on the subjects and the kind of image to be displayed, most results indicate that the diopter values increase after around 15 seconds, when the depth of the presented super-multiview image changes. Clear focal accommodation effect is found especially in Subjects C and F. Since focal accommodation response differs substantially between individuals, this variance in the experimental results is natural.

The mean values of the first and second half of these results are shown in Table 1. Except for the two cases
(gray background), the average diopters go up after 15 seconds.

The results of t-tests are shown in Table 2. Bold p-values are smaller than 0.05. Among them, all but one value is smaller than 0.01, which means that the difference of diopters under the two experimental conditions are statistically significant.

The difference of diopter values induced by super-multiview images, however, is not as wide as the theoretical values. One possible reason of the unstable result is the parallax only in the horizontal direction. Further studies are needed to evaluate whether addition of vertical parallax in addition to horizontal parallax can further induce focal accommodation.

### 5. Conclusion

In this paper, we have proposed a super-multiview autostereoscopic display with full-HD resolution realized by time-division parallax barrier, where the orders of color filters in the two LCD panels are reversed to realize three fold views. The viewing area is expanded in the depth direction by using variable time division to
follow the tracked head position. In addition, human focal accommodation to the super-multiview display we propose is measured. From the experimental results, we have found that it has some effect to induce human focusing, although the effect is dependent on individuals and the kinds of images to be displayed.

Acknowledgement

This work is partially supported by Grant-in-Aid for Scientific Research, JSPS, Japan (17H00750) and JST CREST (JPMJCR18A2).

References

1) Y. Kajiki, H. Yoshikawa and T. Honda, "Hologram-like video images by 45-view stereoscopic display," Proc. SPIE 3012, pp.154-166 (1997)
2) Y. Takaki, "Thin-type natural three-dimensional display with 72 directional images," Proc. SPIE 5664, pp.56-63 (2005)
3) H. Nakanuma, H. Kamei and Y. Takaki, "Natural 3D display with 128 directional images used for human-engineering evaluation," Proc. SPIE 5664, pp.28-35 (2005)
4) Y. Takaki and N. Nago, "Multi-projection of lenticular displays to construct a 256-view super multi-view display," Opt. Express 18(9), pp.8824-8835 (2010)
5) Y. Takaki, K. Tanaka and J. Nakamura, "Super multi-view display with a lower resolution flat-panel display", Opt. Express 19(5), pp.4129-4139 (2011)
6) K. Perlin, S. Paxia, J.S. Kollin, "An autostereoscopic display," Proc. the 27th Annual Conference on Computer Graphics and Interactive Techniques, pp.319-326 (2000)
7) H.J. Lee, H. Nam, J.D. Lee, H.W. Jang, M.S. Song, B.S. Kim, J.S. Gu, C.Y. Park, K.H. Choi, "A high resolution autostereoscopic display employing a time division parallax barrier," SID 2006 Digest, pp.81-84 (2006)
8) G. J. Woodgate, D. Ezra, J. Harrold, N.S. Holliman, G.R. Jones, R.R. Moseley, "Observer-tracking autostereoscopic 3D display systems," Proc. SPIE 3012, pp.187-188 (1997)
9) N.A. Dodgson, "On the number of viewing zones required for head-tracked autostereoscopic display," Proc. SPIE 6055, 60550Q (2006)
10) S.-Y. Yi, H.-B. Chae, S.-H. Lee, "Moving parallax barrier design for eye-tracking auto-stereoscopic displays," Proc. 3DTV Conference 2008, pp.165-168 (2008)
11) J.-E. Gaudreau, "Full-resolution autostereoscopic display with all-electronic tracking system," Proc. SPIE 8288, 82881Z (2012)
12) Q. Zhang and H. Kakeya, "An autostereoscopic display system with four viewpoints in full resolution using active anaglyph parallax barrier," Proc. SPIE 8648, 86481R.1-10 (2013)
13) Q. Zhang and H. Kakeya, "Time-division multiplexing parallax barrier based on primary colors," Proc. SPIE 9011, 90111F (2014)
14) Q. Zhang and H. Kakeya, "A high quality autostereoscopy system based on time-division quadruplexing parallax barrier," IEICE Trans. Electron., Vol. E97-C, No.11, pp.1074-1080 (2014)
15) Q. Zhang and Kakeya, H., "Time-division quadruplexing parallax barrier employing RGB slits," Journal of Display Technology, 12, 6, pp.626-631 (2016)
16) H. Kakeya, K. Okada and H. Takahashi, "Time-Division Quadruplexing Parallax Barrier with Subpixel-Based Slit Control," ITE Trans. on MTA, 6, 3, pp.237-246 (2018)
17) A. Hayashishita and H. Kakeya, "Time-Division Multiplexing Parallax Barrier with Sub-Subpixel Phase Shift," SID Digest of Technical Papers, 49, pp.1515-1518 (2018)
18) H. Kakeya, A. Hayashishita and M. Omimami, "Autostereoscopic Display Based on Time-Multiplexed Parallax Barrier with Adaptive Time-Division," Journal of the Society for Information Display, Vol.26, pp.595-601 (2018)
19) H. Kakeya, "A Full-HD Super-Multiview Display with Time-Division Multiplexing Parallax Barrier" SID 2018 Digest, pp.259-262 (2018)
20) H. Kakeya and Y. Watanabe, "A Full-HD super-multiview display with a deep viewing zone," Proc. IS&T Electronic Imaging 2019, 628.1-6 (2019)
21) Y. Watanabe and H. Kakeya, "Accommodation Response to a Super-Multiview Display Based on Time-Division Multiplexing Parallax Barrier," Proc. IDW 2019, pp.87-90 (2019)