1. Introduction

In recent years, with the advancement of 3D technologies, medical institutions have started to use 3D display systems for endoscopic surgeries in place of conventional 2D systems so that medical staff may obtain depth information during surgeries. Most 3D displays, however, require them to wear special glasses, which often disturb medical operations. To overcome this problem, we need to develop an autostereoscopic display system that enables multiple users to observe high resolution and high quality 3D images simultaneously.

While parallax barrier is one of the simplest and the most well-known method to attain autostereoscopy, the resolution of the observed image is low due to its slit structure. Time-division multiplexing parallax barrier solves this problem by alternating the barrier pattern and the interleaved stereo image synchronously 1)2).

To expand the viewing zone, head-tracking technology has been introduced to follow the observer’s motion 3)4). By detecting the position of the observer’s eyes and changing the barrier pattern and the displayed image accordingly, the viewing zone is expanded in the horizontal direction.

Zhang et al. have proposed time-division quadruplexing parallax barrier, which holds a wider viewing zone for each viewpoint with less crosstalk7)-10). As shown in Fig. 1, they proposed a 4-view system to show 2-view images. When a left-eye image "L" is shown at pixels A and B, and a right eye-image "R" is shown at pixels C and D, we obtain 4 viewpoints aligned as “LLRR.” With this configuration, 3D images without crosstalk are observed when the left eye is between points A and B, and the right eye is between the points C and D.

Based on this system, shift of the slits by subpixel and sub-subpixel unit (smaller than the width of subpixel) has been introduced, which realizes finer control of barrier slits to reduce crosstalk11)12). The fine shift is enabled when the slits are slanted as shown in Fig. 2, which also reduces moiré caused by the layered panels without destroying stereoscopy. The viewing zone in the depth direction has been expanded by changing the number of time-division adaptively as shown in Fig. 313).

The persisting problem of the conventional parallax barrier systems is that it allows only one observer, which limits the range of application regardless of its low cost and thin structure. Here we propose a method to realize...
autostereoscopy for two observers simultaneously based on fractional time-division multiplexing. As Fig. 3 shows, adaptive control of time division changes the width of viewing zone in the same depth. Adaptive fractional time-division enables fine width adjustment of viewing zone, which copes with continuous change of interval between the two observers so that they can keep on seeing the same stereoscopic image.

This paper is organized as follows. In Section 2, we explain the mechanism of fractional time-division multiplexing. In Section 3, we explain how an autostereoscopy for two viewers are realized by adaptive time-division. The result of experiments using a prototype system is explained in Section 4. The viewing zone without crosstalk is analyzed theoretically in Section 5 and the paper is concluded in Section 6.

2. Fractional Time Division

Figure 4 shows the examples of fractional time-division multiplexing parallax barrier 14]. For example, in case of 10/3 time-division, each image unit is composed of 10 subpixels, where the left-eye and the right-eye images consist of 5 subpixels respectively. As for the parallax barrier, 3-subpixel (1-pixel) wide slits and 7-subpixel wide barriers are repeated alternately.

The positions of the slits and the interleaved image are shifted at every frame and after 10 frames every subpixel becomes a slit three times each. The detail of 10/3 time-division is shown in Figs. 5 and 6.

In the same way, 3-subpixel slits and 11-subpixel barriers are repeated alternately in the 14/3 time-division barrier, while 3-subpixel slits and 13-subpixel barriers are repeated alternately in the 16/3 time-division barrier. The width of the interleaved left-eye and right-eye images is 7 subpixels wide in 14/3 time-division and is 8 subpixels wide in 16/3 time-division respectively. In this way, the number of time-division is adjusted in a finer way, which realizes smoother width change of viewing zone.

One possible problem with the fractional time-division
is emergence of perceived flickers due to its long periodical cycle. Table 1 shows the positions of slits at different time (frame number) \( t \). When the shift of slits becomes larger so that the positions of slits in the next frame may come closer to the center of the barrier part in the current frame, flicker becomes less noticeable because of the after-image effect\(^{14}\).

In this paper, we use 10/3, 14/3, and 16/3 fractional time-division combined with conventional quadruplexing (12/3).

3. Autostereoscopy for Two Observers

We use the fractional time-division multiplexing to realize an autostereoscopic display for multiple observers by using active parallax barrier\(^{15}\). When two persons observe a stereo image with the conventional system simultaneously, one observer can obtain correct stereoscopy, while the other may experience a reverse viewing where the right-eye image and the left-eye image are exchanged.

To avoid this problem, we control the width of viewing zone in accordance with the distance between the two observers to maintain stereoscopy for the two observers simultaneously as shown in Fig. 7. Here the widths of the areas where only the left-eye image and the right-eye image are observed are denoted as \( \Delta L \) and \( \Delta R \) respectively, while the interval between these areas is denoted as \( \Delta \text{Eye} \).

The simplest way to change the width of viewing zone is to change the number of time-division as explained above. If we use the optimum number of time-division to place the left eyes and the right eyes of the two observers in the correct viewing zone, stereoscopy is maintained for the two observers.

To keep proper interval of viewing zone in accordance with the distance between observers, various number of time-division should be chosen to adjust the width of viewing zone. To attain this, we can use fractional numbers of time-division in place of integer time-divisions.

Here let the number of time division be \( T \) and let the width of the single viewing unit (\( \Delta L + \Delta R + 2 \Delta \text{Eye} \)) for that time division be \( W_T \). When the distance between the centers of two observers is \( d \), we choose the number of time division \( T \) so that \( d/W_T \) may be closest to an integer.

As shown in Fig. 8, the distance \( d \) between the two observers must satisfy

\[
(nW_T - \Delta d < d < nW_T + \Delta d) \tag{1}
\]

to ensure that the two observers can observe a proper stereoscopic image, where \( \Delta d \) is the margin where the second observer can move within the viewing zone without crosstalk when the first observer is on the edge of viewing zone. Let \( P \) be the interpupil distance of observers. When \( P > \Delta \text{Eye} + \Delta L = \Delta \text{Eye} + \Delta R \), \( \Delta d = \Delta \text{Eye} + \Delta L + \Delta R - P \) holds. Otherwise \( \Delta d \) is given by \( \min(P - \Delta \text{Eye}, \Delta L) \) or \( \min(P - \Delta \text{Eye}, \Delta R) \).

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Table 1 Conditions where \( n \)-th subpixel is open at \( t \)-th frame for each time-division.

| Time Division | Conditions where \( n \)th subpixel is open at \( t \)th frame |
|--------------|-------------------------------------------------------------|
| 10/3         | \((n - 3t) \text{ mod } 10 < 3\)                           |
| 12/3         | \((n - 3t) \text{ mod } 12 < 3\)                           |
| 14/3         | \((n - 5t) \text{ mod } 14 < 3\)                           |
| 16/3         | \((n - 7t) \text{ mod } 16 < 3\)                           |

**Fig. 6** Time sequence of interleaved image in 10/3 time division multiplexing.

**Fig. 7** Adaptive width change of viewing zone to keep stereoscopy.
At every frame, we track the eyes’ position of each observer and calculate the distance between them. We select the best number of time division for that distance and apply it to the display system. We also move the slit horizontally to fit to the positions of the observers.

Here note that the barriers and the slits are slanted. When we calculate the horizontal distance $d$ between the two observers, the two heads should be in the same height, for the viewing zone in the horizontal direction moves along the slanted barrier in the vertical direction. When the heads of the observers are not in the same height, we calculate the horizontal distance $d$ by virtually shifting one of the heads along the inclination angle of the slits so that the two heads are aligned in the same height as shown in Fig. 9.

\[
\Delta d = \min(\Delta L, \Delta L + \Delta \text{Eye} + \Delta R - P)
\]

Then we decide the number of time division based on the virtual horizontal distance $d$ when the two heads are supposed be at the same height.

### 4. Result

We have tested the proposed method with a prototype time-division multiplexing system. The prototype system was composed of a pair of 23.8 inch LCD panels (AUO M238DTN01.3, 2560 × 1440 pixels), where the pixel pitch $p$ was 0.206 mm.

A directional diffuser was inserted to keep the interval $L_d$ between the two panels as wide as 5 mm, while the barrier pattern and the diffuser were both inclined by $\tan^{-1} 1/6$ to suppress moiré. The slits were 3 subpixels wide and we used 10/3, 12/3 (= 4), 14/3, and 16/3 time-divisions adaptively. We used Kinect V2 to track the eyes of two observers at 30 fps.

We have confirmed how the crosstalk was suppressed when two viewers observed a stereoscopic image simultaneously with the prototype system. Although autostereoscopy was maintained most of the time for both of the viewers as expected, the second observer perceived crosstalk sometimes during the change of the distance between the two observers, which suggests that the proposed system is not sufficient enough to eliminate crosstalk under all conditions.

Figure 10 shows the pictures when a white image is shown to the left eyes and a black image is shown to the right eyes. Here the viewer on the right sits still while the other viewer moves to the right.

The black and white stripes are supposed to be generated so that the black stripes may overlap with the right eyes of the viewers, while the white stripes may overlap with the left eyes of the viewers. The widths of black stripes, white stripes, and gray areas correspond to $\Delta R$, $\Delta L$, and $\Delta \text{Eye}$ respectively. If the black image is replaced by a right-eye image and the white image is
replace by a left-eye image, stereoscopy is realized for the two viewers. As the figure shows, the position and the width of viewing zone are adjusted as the observer on the left moves to keep proper stereoscopy for both observers.

When the number of time-division increases, the luminance of image drops because the aperture ratio of slits decreases. To maintain stable luminance, the power of backlight should be controlled to have a higher luminance when the number of time-division becomes larger.

5. Viewing Zone

In this section, we analyze the viewing zone of the prototype system introduced in the previous section.

The theory on the viewing zone without crosstalk given by time-division multiplexing parallax barrier has already been established \cite{11,13}. In the prototype system, the width of the slit is equal to the pixel pitch \( p \) because the slit is 3-subpixel wide. In this case, the width of viewing zone is given by

\[
\Delta L = \Delta R = (2\mu - (1 + \mu)\alpha - 2\beta)pL_D/L_d, \quad (2)
\]

\[
\Delta \text{Eye} = ((1 + \mu)\alpha - \mu + 2\beta)pL_D/L_d, \quad (3)
\]

where \( \mu = T/2 \), \( L_D \) is the distance between the front display panel and the observers, \( \alpha \) is the aperture ratio of slit, and \( \beta \) is the minimum phase shift, which is 1/12 when the slit is 3 subpixel wide and the inclination angle of slit is \( \tan^{-1} 1/6 \). The aperture ratio is given by \( \alpha = 1.1 \) according to the previous study \cite{11,13}. The interval between the LCD panels \( L_d \) is 5 [mm] in the prototype system. As equations (2) and (3) show, \( \Delta L, \Delta R, \) and \( \Delta \text{Eye} \) are dependent on \( T \) through \( \mu \).

Here we assume \( L_D = 700 \) [mm]. Then the theoretical values of \( \Delta L, \Delta R, \) and \( \Delta \text{Eye} \) for each time division are shown in Table 2, where 10/3 time-division is excluded because no viewing zone is secured for a viewer whose interpupil distance \( P \) is 63 [mm] at \( L_D = 700 \). (10/3 time-division becomes effective when \( L_D \) is larger.)

We define the crosstalk level as shown in Fig. 11. When the observer is in the best viewing area where the left eye is located in the \( \Delta L \) range and the right eye is located in the \( \Delta R \) range, the crosstalk level is 0%. In the worst case where the views are reversed, the crosstalk level is 100%. In between, we assume that the crosstalk level increases linearly from 0% to 100%.

Let \( \Delta D \) be the distance from the observer’s current position to the closest viewpoint without crosstalk. By taking Fig. 8 into account, \( \Delta D \) is written in the form

| \( T \) | \( \Delta \text{Eye} \) [mm] | \( \Delta L, \Delta R \) [mm] |
|-------|----------------|----------------|
| 12/3  | 42.30          | 15.38          |
| 14/3  | 43.26          | 24.03          |
| 16/3  | 44.22          | 32.69          |
Since the crosstalk level is supposed to increase linearly in $\Delta E_y$ until it reaches 100%,

$$\Delta D = \min[\max\{d - \frac{d}{W_f}\text{floor}\left(\frac{d}{W_f}\right) - \Delta d, 0\},$$

$$\max\{W_f\text{ceiling}\left(\frac{d}{W_f}\right) - d - \Delta d, 0\}]. \quad (4)$$

Since the crosstalk level is supposed to increase linearly in $\Delta E_y$ until it reaches 100%,

$$\text{Crossstalk level} = \min(\Delta D/\Delta E_y, 1) \quad (5)$$

holds. Based on the above equations, we calculate the crosstalk levels given by different time-divisions as the distance between two observers varies, as shown in Fig. 12. Here we assume that the interpupil distance $P$ is 63 mm. When we choose the number of time-division that gives the minimum crosstalk level, the crosstalk level at each inter-observer distance is obtained as shown in Fig. 13.

As this figure shows, some crosstalk appears as the distance changes. This is considered to be the cause of the crosstalk observed in the prototype system.

One way to further decrease the minimum crosstalk level is to use finer control of time-division as shown in Fig. 14. Here $12/3, 13/3, 14/3, 15/3, 16/3, 17/3,$ and $18/3$ time-division multiplexing modes are used. The crosstalk level after choosing the best number of time-division among the seven modes is maintained at 0% when the inter-observer distance is from 250 mm to 800 mm, as shown in Fig. 15.

When the numerator of fractional time-division is an odd number, the widths of the interleaved images for the left and the right eye are not evenly divided at each scan line. When the inclination of barrier is $\tan^{-1} 1/6$, however, the widths can be alternated in each scan line.
6. Conclusion

In this paper, we have proposed the adaptive fractional time-division multiplexing parallax barrier method that allows two observers to view stereo images simultaneously. The two observers can be positioned in the proper viewing zone at the same time by changing the width of viewing zone, which can be achieved by adaptive time-division multiplexing. The viewing zone without crosstalk for the second viewer is evaluated theoretically and it is confirmed that finer control of time-division is needed to suppress the emergence of crosstalk entirely.

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