Depth Perception of Multiplication-Type Multi-Layer Display by Binocular and Motion Parallaxes

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ABSTRACT

The depth perception of multiplication-type depth fused 3D displays was clarified using calculations. Even though of non-linearity in overlapping region luminance, front observations were natural. However, dark objects caused large depth distortion in oblique observations of motion parallax in these displays.

1 INTRODUCTION

Multi-layer displays are volumetric and quantized in the depth direction. Data quantity transferred to these devices are reduced due to discretization. Though the viewing zone is restricted, physiological factors of stereoscopic vision such as binocular parallax, motion parallax, convergence, and accommodation are satisfied well within the viewing zone. Therefore, their displayed images are highly compatible with human vision and can be applied to not only direct view displays, depth fused 3D (DFD) displays [1], tensor displays, etc., but also to head mounted displays.

There are different types of multi-layer displays, from the viewpoint of luminance calculation of overlapping pixels. In addition-type displays, the luminance of overlapping pixels is the sum of each pixel luminance. They can be constructed by synthesizing two or more screen images using half mirrors or by stacking transparent screens with angular selectivity. In multiplication-type displays, the luminance of overlapping pixels is the product of each pixel luminance. They can be constructed using a stack of LCD panels or printed transparent films [2]. By stacking LCD panels eliminating internal polarizers, the calculation characteristics become similar to the aforementioned type [3].

Screen images can be generated using two types of methods. The first is through image sharing. An image is projected and shared to screens depending on the depth of the image. It is used in DFD displays. The other kind is optimization calculations. Screen images are optimized to minimize the error of specific viewpoint images, and it is used in tensor displays.

The depth perception of the DFD displays of addition-type and using a stack of LCD panels without an internal polarizer has been clarified. However, that of the multiplication-type displays, which are often used in tensor displays, has not. In this paper, we clarify the impact of the nonlinear effect of luminance multiplication for depth perception using calculations.

2 PERCEPTION OF MULTI-LAYER DISPLAYS

2.1 Edge Perception

Figure 1 shows the typical conditions of observing multi-layer displays. In them, screen images are shifted depending on the viewing position. Therefore, edges become slightly double. Because the depth is perceived using a precise edge position, the perception of a double edge is important. In phenomenalism, the perceived edge is at a maximum gradient of luminance profile after applying a Gaussian low-pass filter [4,5], and it is the same as a zero-cross point after applying the Laplacian of a Gaussian[6]. Theoretically, it is the addition of a trigonometric function of a spatial frequency component [7]. SSAA (super sampling antialiasing) is a very precise approximation when the width of the doubled edge is narrower than the period of the cut-off spatial frequency of human vision (almost 3–5 arcmin) [8].

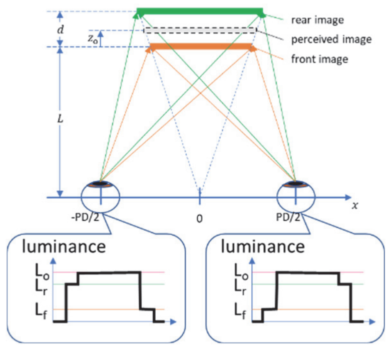


Fig. 1 Retinal images when a stacked display is observed.

Figure 2 shows a luminance profile of a retinal image and the calculation of the effective edge position using SSAA. Disparities in the rear image from the front image Δ_L and Δ_R can be expressed using viewing position x, distance from front screen z_o, and separation between front and rear screens d:

$$\Delta_L = \Delta_R = \frac{d}{z_o + d} x.$$

Disparities of perceived edges from the front image edges δ_L and δ_R satisfy the following equations due to

SSAA.

$$\Delta_L L_r = \delta_L L_o$$
$$\Delta_R L_f = (\Delta_R - \delta_R) L_o$$

Therefore, the effective edge positions, which are indicated by the blue lines in the figure, are

$$\delta_L = \frac{L_r}{L_o} \frac{d}{z_o + d} x$$
$$\delta_R = \left(1 - \frac{L_f}{L_o}\right) \frac{d}{z_o + d} x.$$

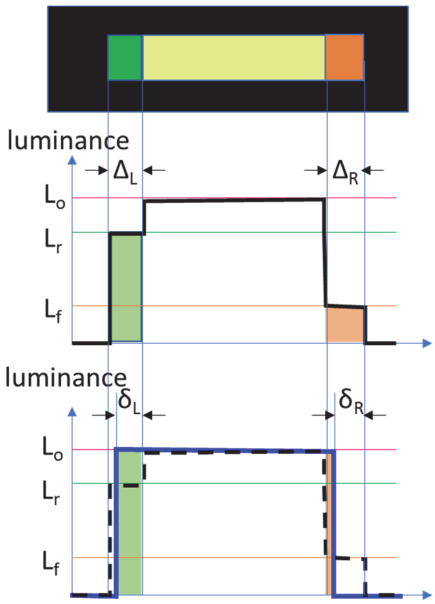


Fig. 2 Luminance profile of an observed image for an addition-type multi-layer display.

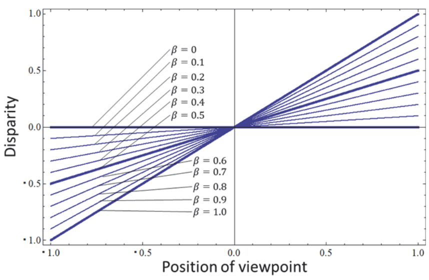


Fig. 3 Disparity induced by motion parallax for an addition-type multi-layer display.

2.2 Depth Perception in Addition-Type Displays

Because the luminance calculation of an addition-type multi-layer display is $L_o = L_r + L_f$,

$$\delta_L = \delta_R = \frac{d}{z_o + d} \frac{L_r}{L_o} x.$$

Using normalized depth of displayed object $\beta = z/d$, front and rear image luminance of the object can be expressed as $L_f = (1 - \beta) L_o$ and $L_r = \beta L_o$ in a DFD display, respectively. Therefore,

$$\delta_L = \delta_R = \frac{d}{z_o + d} \beta x.$$

Figure 3 shows the disparity of the edges depending on the viewing position. In other words, this figure shows the disparity induced by motion parallax. As can be seen, the tilts of the lines are in proportion to the normalized depth β, and they radiate from the origin. Thus, exact motion parallax is reproduced precisely.

Figure 4 shows the perceived depth in accordance with binocular parallax. The binocular parallax is the difference of the disparities, shown in Fig. 3, at the positions of the pupils. Because tilts of the plots are independent of the position of the viewpoint, the perceived depth is exact in the viewing zone.

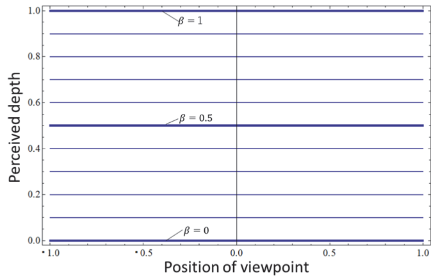


Fig. 4 Perceived depth in accordance with binocular parallax of an addition-type multi-layer display.

3 MULTIPLICATION-TYPE DISPLAYS

Because the luminance calculation of a multiplication-type multi-layer display is $L_o = L_r L_f$, images are shared to be the optical density of screen images equal to normalized depth. Therefore,

$$L_f = {L_o}^{1-\beta}$$
$$L_r = {L_o}^{\beta}.$$

The luminance profile becomes as shown in Fig. 5. Because the luminance is always decreased by screen images in a multiplication-type display, the background is white. Disparities of the edge position should be satisfied due to SSAA:

$$\Delta_L (L_r - L_o) = (\Delta_L - \delta_L)(L_{max} - L_o)$$
$$\Delta_R (L_f - L_o) = \delta_R (L_{max} - L_o).$$

Because Δ_L and Δ_R are the same as those in the addition-type display, they can be expressed by normalizing luminances with L_{max}:

$$\delta_L = \begin{cases} \left(1 - \frac{{L_o}^{\beta} - L_o}{1 - L_o}\right) \frac{d}{z_o + d} x & x \le 0 \\ \frac{{L_o}^{1-\beta} - L_o}{1 - L_o} \frac{d}{z_o + d} x & x \ge 0 \end{cases}$$

$$\delta_R = \begin{cases} \frac{{L_o}^{1-\beta} - L_o}{1 - L_o} \frac{d}{z_o + d} x & x \le 0 \\ \left(1 - \frac{{L_o}^{\beta} - L_o}{1 - L_o}\right) \frac{d}{z_o + d} x & x \ge 0 \end{cases}.$$

Please note that characteristics of the edge position are asymmetrical.

Figure 6 shows the relationships between the disparity and viewing position to determine the characteristics of motion parallax. When the luminance of an object is high, the characteristics are similar to Fig. 3, and the motion parallax is mostly exact (Fig. 6(a)). However, as shown in Fig. 6(b), when the luminance of the object is dark, the effects of asymmetricity become prominent.

Figure 7 shows the perceived depth in accordance with binocular disparity. The horizontal axis is normalized by inter pupil distance. As shown in Fig. 7(a), when the luminance of an object is bright, the perceived depth is mostly exact. However, for a darker object, large distortion occurs in depth perception except when the viewpoint is just in front ($x = 0$), as shown in Fig. 7(b).

Figure 8 shows the relationship between the assigned display depth and perceived depth. For a front observation (Fig. 8(a)), the characteristics were linear. However, for an oblique observation, they were nonlinear for dark objects (Fig. 8(b)).

A typical example of nonlinearity effect of multiplication type is shown in Fig. 9 using anaglyph. Top and bottom squares are objects at front screen. Middle squares are stacked images of different viewpoints. When viewpoint is just in front ($x = 0$), the middle square is parallel to the paper surface. Moving viewpoints to $x = \pm PD/2$, tilt angle of the middle square increase. When $|x| > PD/2$, tilt angle of the middle square is constant unless double edge is observed.

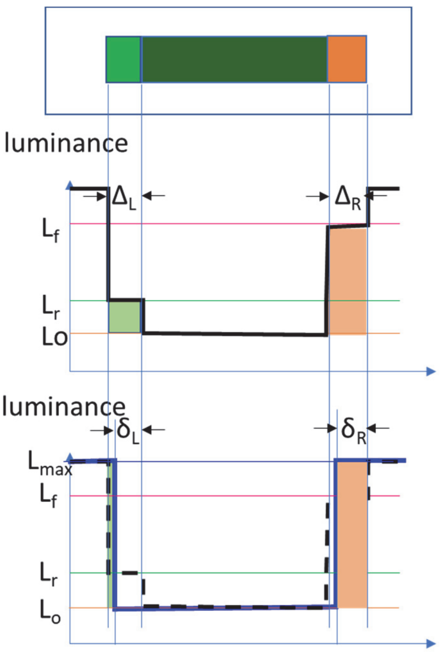
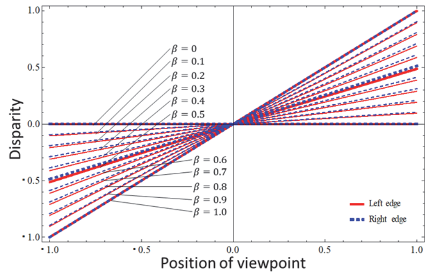
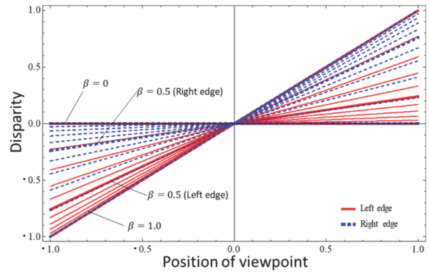


Fig. 5 Luminance profile of observed image for a multiplication-type multi-layer display.

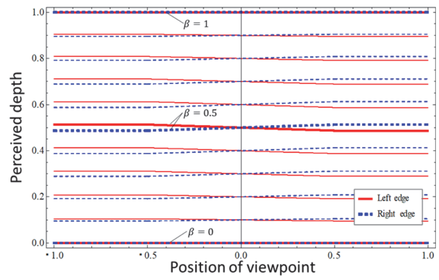


(a) Bright object ($L_o = 0.9$)

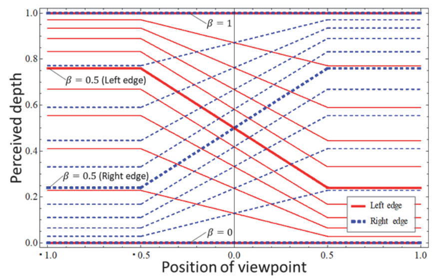


(b) Dark object ($L_o = 0.1$)

Fig. 6 Disparity induced by motion parallax for a multiplication-type multi-layer display.

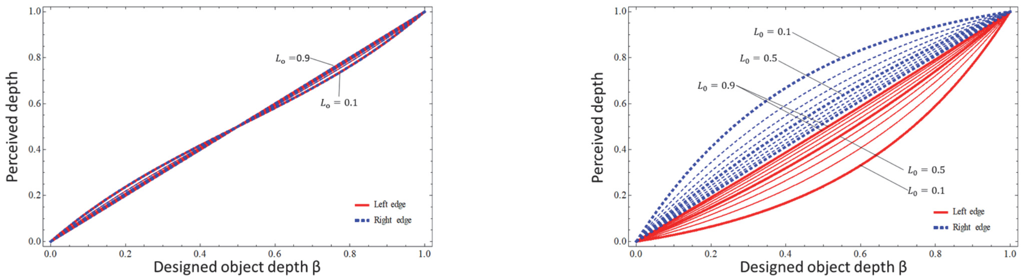


(a) Bright object ($L_o = 0.9$)



(b) Dark object ($L_o = 0.1$)

Fig. 7 Perceived depth by binocular parallax of a multiplication-type multi-layer display.



(a) Front observation ($x = 0$) (b) Oblique observation ($x = 0.5$)

Fig. 8 Dependence on perceived depth at different viewing positions.

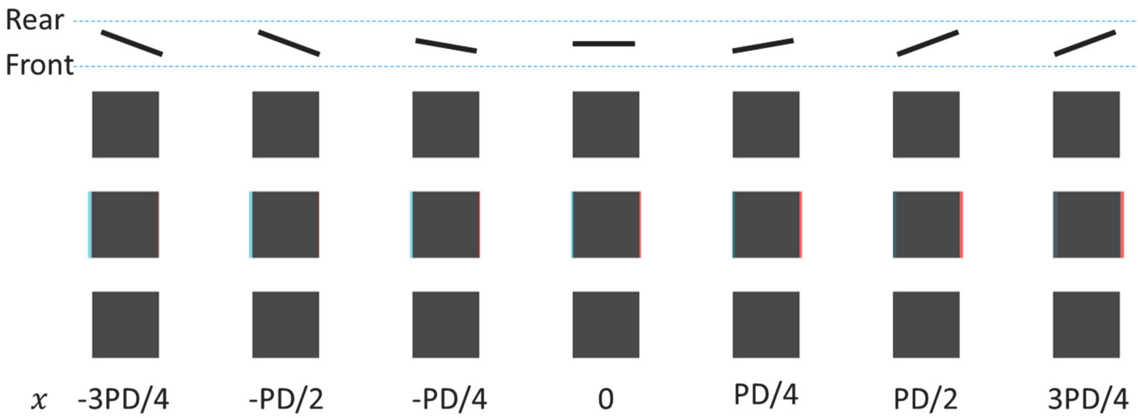


Fig. 9 Observed images at different positions of viewpoint x. Top and bottom squares are at the depth of front screen. Middle squares are images on multiplication type display when $L_o = 0.1$ and $\beta = 0.5$. Using glasses of anaglyph, middle squares are tilted for oblique vision as indicated by lines at top.

4 CONCLUSIONS

We clarified the depth perception of multiplication-type DFD displays. For front observations, non-linearity was canceled well, and natural 3D images were observed. However, oblique observation produced large distributions for the depth direction. Our results will contribute to developing a multiplication-type display with a wide viewing zone and natural motion parallax.

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