Dependence of 3D Image Contrast on Ceiling/Background Illumination and Screen Reflectance in a Volumetric Display using a Helical Rotating Screen

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ABSTRACT

The equations for calculating 3D image contrast considering illumination from the ceiling/background and screen reflectance were derived. We also measured contrast on our volumetric 3D display using a helical rotating screen. The effects of ceiling/background illumination and screen reflectance on the 3D image contrast were clarified.

1 Introduction

Binocular stereo displays are currently the most popular 3D systems [1], [2]. However, they exhibit apparent weaknesses, such as only a single or, at most, a limited number of viewpoints and inability of providing side or backside views of objects. They often require observers to wear special glasses. On the contrary, the volumetric 3D displays, which provide light pixels in 3D spaces, can offer observation from universal directions without a use of special eyeglasses [3], [4].

We focused on an advanced volumetric display method, wherein multiple layers of cross-sectional images are formed on a rotating helical screen by a projector synchronized with the rotation speed of the screen [5-7]. However, this 3D system has a potential problem in that invisible regions are partially assumed in the cylindrical display volume formed by the rotating helical screen [8-10].

Using a light path simulation method, we proved a possible enlargement of the visible region using a transparent screen [11]. However, we also found that the transparent screen brings reduction of brightness and results degradation of image visibility. In general, image contrast is a dominant parameter that controls image visibility.

In this study, we derived equations for calculating the contrast of our 3D system. We also preformed actual measurements of contrast using opaque and transparent helical screens on our prototype 3D display. Thus, we clarified the effects of ceiling/background illumination and screen reflectance on the contrast of 3D images on a 3D display with a rotating screen.

2 Construction of our 3D Display System

The arrangement of the 3D display system is illustrated in Fig. 1. This 3D display system consists of a digital mirror device (DMD) projector (ViALUX: STAR-07 RGB,

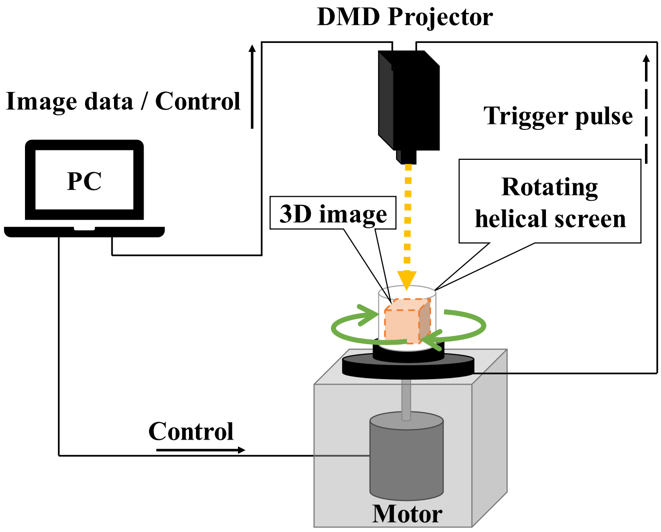
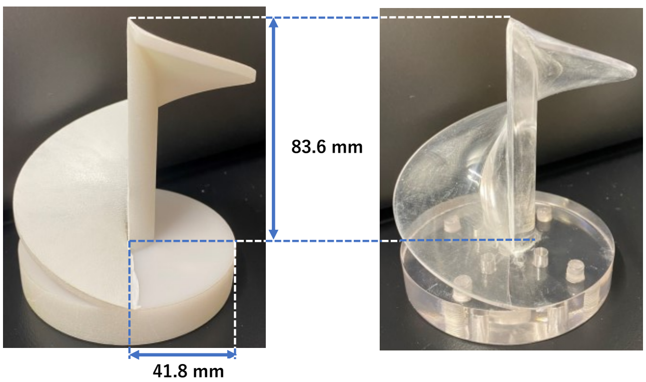


Figure 1. Arrangement of the proposed 3D display system

1024×768 pixels, throw ratio = 1.8) and a helical screen of opaque or transparent type (Fig. 2). The projected cross-sectional images were synchronized with trigger pluses from the rotating helical screen. The DMD projector formed multiple layers of cross-sectional images on a rotating helical screen. The rotation speed of the screen was set to 1800 rpm, which was determined to be a sufficient for



(a) Opaque type **(b)Transparent type**

Figure 2. Types of helical screens

afterimages without flickering. Three directional images were formed by the accumulated afterimages of the projected cross-sectional images, and up to 128 layers of images were formed in our prototype. The illuminance on the screen by the projector used in our prototype system measured when the illuminance meter was pointing toward the ceiling (Fig. 3) and the projections were full white and full black. The measured maximum and minimum illuminance were E_{Pmax} = 10200 lx and E_{Pmin} = 6.28 lx respectively. Typical images obtained using our experimental 3D system are shown in Fig. 4, where the projected image of a human head can be viewed three-dimensionally from a universal direction.

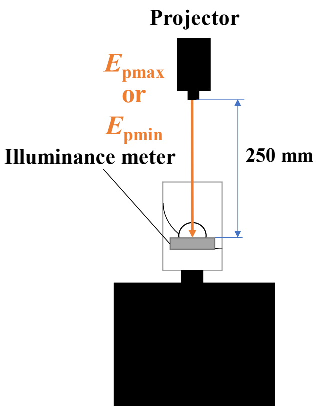
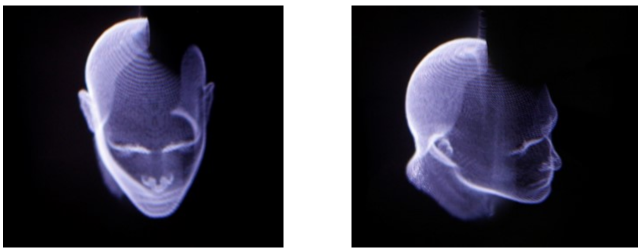


Figure 3. Method of measuring projector illuminance



(a) Front view **(b) Left view**

Figure 4. Typical 3D images

3 Derivation of contrast in this type of 3D display

The contrast C of a display is generally expressed as the ratio of the luminance of the white screen display (highest luminance) to that of the black screen display (lowest luminance) [12]. The maximum luminance in our 3D display is the luminance value when the projector displays a "white" screen, and the minimum luminance is the luminance value when the projector displays a "black" screen. Therefore, the contrast C_1 of our 3D display can be expressed by Eq. (1), considering ceiling/background illumination.

$$C_1 = \frac{L_{Pmax} + L_{down} + L_{back}}{L_{Pmin} + L_{down} + L_{back}}, \qquad (1)$$

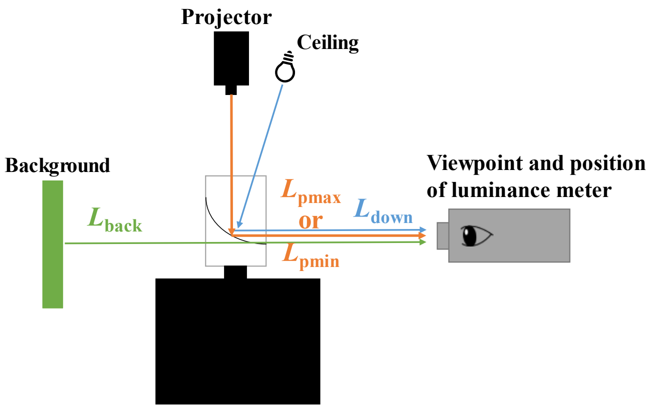


Figure 5. Parameters for determining contrast of the display in this 3D system

where L_{Pmax} and L_{Pmin} are the luminances of the reflected light from the screen when the illuminance of the projector is maximum and minimum (leaked light), respectively, L_{down} is the luminance of the reflected light from the screen provided by the ceiling light, and L_{back} is the luminance of the background light (Fig. 5).

Assuming that the reflective surface is an even uniform diffuser, the luminance L of the reflective surface can generally be expressed as in Eq. (2) [13].

$$L = \frac{\rho E}{\pi}, \qquad (2)$$

where E is the illuminance on the reflective surface and ρ is the reflectance of the reflective surface. We assumed the helical screen used in the 3D display to be an even uniform diffuser, E to be the illuminance on the helical screen and ρ to be the reflectance of the helical screen in Eq. (2). Substituting Eq. (2) into Eq. (1), the contrast C_1, offered by the 3D display using a helical screen as an even uniform diffuser, can be calculated by obtaining the illuminance of the screen E_{Pmax}, E_{Pmin}, E_{down} and the screen reflectance ρ, as shown in Eq. (3).

$$C_1 = \frac{\frac{\rho E_{Pmax}}{\pi} + \frac{\rho E_{down}}{\pi} + L_{back}}{\frac{\rho E_{Pmin}}{\pi} + \frac{\rho E_{down}}{\pi} + L_{back}} \qquad (3)$$

Equation (3) suggests that contrast C_1 decreases as screen reflectance ρ decreases. Therefore, the contrast of the 3D image displayed on the transparent screen was assumed to be lower than that of the opaque type because the reflectance of the transparent screen was lower than that of the opaque type.

The contrast C_2 when assuming the absence of background illumination (L_{back} = 0) can be expressed by Eq. (4) as a simplified case of Eq. (3).

$$C_2 = \frac{E_{Pmax} + E_{down}}{E_{Pmin} + E_{down}} \quad (4)$$

Equation (4) suggests that contrast C_2 can be expressed using only the illuminance of the projector and ceiling in the absence of background illumination. Equation (4) significantly suggests the contrast C_2 to be regarded as independent of the screen reflectance for the negligibly weak background illumination.

4 Calculation of contrast in our 3D display using measured luminance values

The contrast C_1 of this 3D display was calculated using Eq. (1) in the absence of ceiling illumination (L_{down} = 0). A luminance meter was set to point toward the center of the screen (Fig. 5). The luminance values of the display were measured using a luminance meter when all white (highest total luminance = $L_{Pmax} + L_{back}$) and all black (lowest total luminance = $L_{Pmin} + L_{back}$) were displayed in the presence of background illumination. The contrast for various background illumination was calculated using Eq. (1). Figure 6 shows the contrast C_1 obtained when the ceiling lights were turned off. The horizontal axis represents the background illuminance measured when the illuminance meter was directly pointing toward the background (Fig. 7 (a)). Contrast C_1 was lower for the transparent screen than for the opaque screen in the presence of the background illumination. The measured results are as suggested by Eq. (3).

On the contrary, the contrast C_2 of this 3D display in the absence of background illumination (L_{back} = 0) was also calculated using Eq. (1). The luminance values of the display were measured using a luminance meter set to point toward the center of the screen (Fig. 5) when all white (highest total luminance = $L_{Pmax} + L_{down}$) and all black (lowest total luminance = $L_{Pmin} + L_{down}$) were displayed in the presence of ceiling illumination. The contrast for various ceiling illuminations was calculated using Eq. (1). Figure 8 shows the contrast C_2 of this 3D display in the absence of background illumination. The horizontal axis represents the illuminance measured when the illuminance meter was pointing toward the ceiling (Fig. 7 (b)). The contrast values of the transparent and opaque screens were nearly equal in the absence of background illumination. Here, the reflectance of transparent and opaque screens was naturally different. Therefore, the measured contrast in the absence of background illumination was independent of the reflectance of the screen, as suggested by Eq. (4).

These results suggest a possibility of that improving the visible range, as shown in the simulation results of our previous report, without decreasing the contrast, by darkening the background when using a transparent screen.

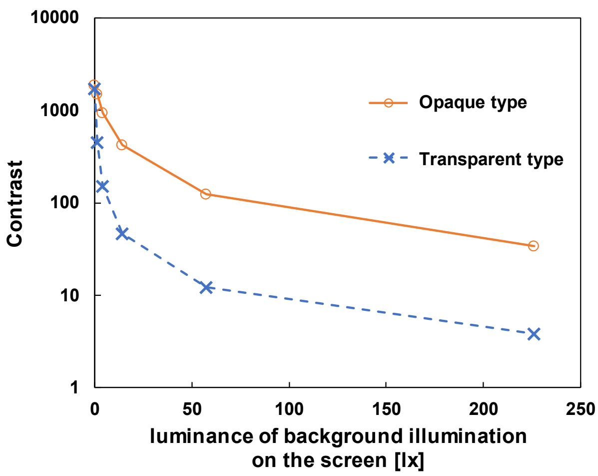
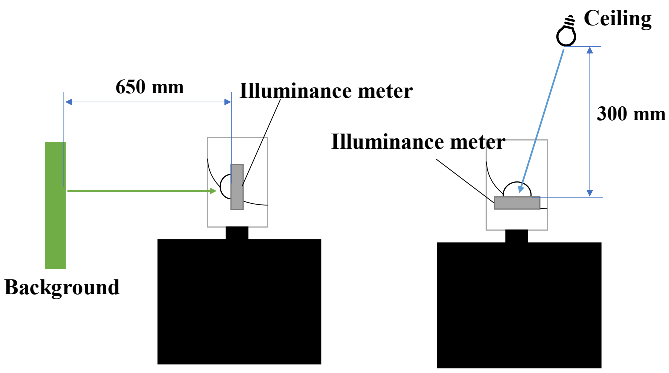


Figure 6. Background illumination dependence of 3D image contrast



(a) Background illuminance **(b) Ceiling illuminance**

Figure 7. Method of measuring each illuminance

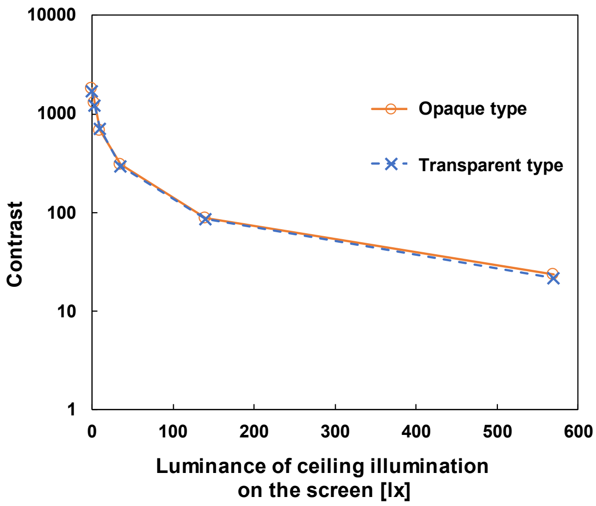


Figure 8. Ceiling illumination dependence of 3D image contrast

5 Conclusions

(1) We derived equations for calculating the image contrast of our 3D display using ceiling/background illuminance and screen reflectance.

(2) The derived equation suggested the following: 1) The contrast of this display decreases as the screen reflectance decreases, when the background illumination of the rotating screen is bright. 2) The contrast of this display is unaffected by screen reflectance in the presence of only ceiling illumination, without a brigh t background beyond the rotating screen.

(3) The measured results of contrast in our 3D display were as suggested by the derived equations when calculated under various illumination conditions and two different reflectances of the screen.

(4) These results show that the visible region enlargement using the transparent screen, as shown in the simulation results of our previous report, can be realized without contrast reduction if the screen background is dark.

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