3D Aerial Display Combining Optical See-Through Aerial Imaging by Retro-Reflection with Depth-Fused 3D Display

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ABSTRACT

Aerial 3D display can be achieved using a Depth-fused 3D display combining an optical see-through aerial imaging by retro-reflection. Furthermore, our proposed aerial 3D display allows the observer to perceive the 3D image even at wide range of observation distances from about 2 meters to over 5 meters.

1 Introduction

In recent years, various technologies that can form images in the air have been proposed and have attracted much attention. One such technology is aerial imaging by retro-reflection (AIRR) [1]. AIRR allows users to view images floating in the air without the need for 3D glasses. AIRR features wide viewing angles, large-size scalability and low cost and mass-productive optics. One problem with the AIRR is that it does not allow the user to check on the user from the facing side. This problem has been solved by optical see-through AIRR [2] by reviewing the optical system of the AIRR.

The AIRR and optical see-through AIRR forms a 2D screen in the air, which is the same as the display screen. By using light source with 3D structure, aerial image with depth structure can be displayed. However, as depth is inverted at 3D aerial image, it causes problems such as occlusion contradiction. Depth-fused 3D (DFD) display [3] is comparatively adequate to an aerial 3D display by stacking two aerial display optics [4], although inverted problem and complicated structure still remain.

To solve this inverted problem, we propose an aerial DFD display with a simpler structure and at a lower cost by using an optical see-through AIRR and opposite-side display of AIRR, that is, front and rear images in DFD display correspond to aerial image in AIRR and opposite-side display. Our new optical system can obtain aerial images with various depths using a DFD display that combines an optical see-through AIRR and an opposite-side display.

2 Principle

2.1 Principle of AIRR

AIRR is an aerial imaging technology that uses a light source, beam splitter, and retro-reflector. The principle of AIRR is shown in Fig. 1. A part of the light emitted from the light source is reflected by the beam splitter. That light enters the retro-reflector and is retro-reflected to the beam splitter. A part of the retro-reflected light returns to the light source, and the remainder is transmitted through the beam splitter. The transmitted light is focused on a position that is plane-symmetrical to the light source with respect to the beam splitter to form an aerial image.

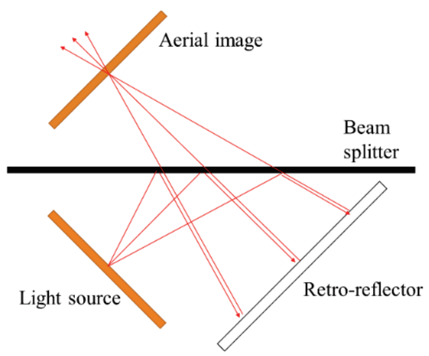

Fig. 1 Principle of aerial imaging by retro-reflection (AIRR).

2.2 Principle of Optical See-Through AIRR

The optical see-through AIRR used in this experiment is based on the p-AIRR [5] principle. The p-AIRR is a technology that changes the beam splitter of the AIRR component to a reflective polarizer and uses an additional quarter-wave retarder to form an aerial image. The optical see-through AIRR differs from the AIRR configuration in that the retro-reflector is located on the top panel. The principle of optical see-through AIRR used in this experiment is shown in Fig. 2. The p-polarized light emitted from the light source is incident on the reflective polarizer. This light is transmitted because it is parallel to the reflective polarizer. The transmitted light passes through a quarter-wave retarder, which gives the light a phase delay of π/2 and makes it circularly polarized. Circularly polarized light enters the retro-reflector, is retro-reflected, and again transmitted through the quarter-wave retarder. The result is linearly polarized light that is rotated 90° from that emitted from the light source. The light reflects on the reflective polarizer. The reflected light converges to the position of plane symmetry of the light source with respect to the

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reflective polarizer.

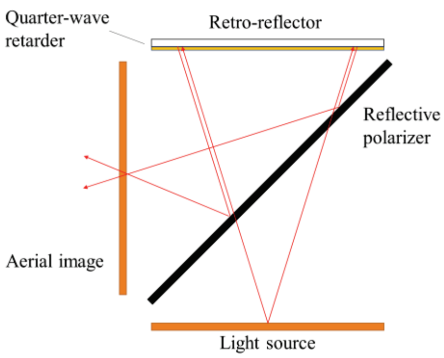

Fig. 2 Principle of optical see-through AIRR.

2.3 DFD Display

Conceptual diagram of the DFD display is shown in Fig. 3. The DFD display consists of two transparent 2D displays arranged in parallel, front and rear, in the depth direction from the midpoint of observer's eyes. The displayed image is overlapped on the front and rear displays as a projected image from midpoint of observer's eyes**.** The overlapped image is perceived as a single image fused in the depth direction. Perceived depth position can be changed continuously according to the luminance ratio of the front and rear images.

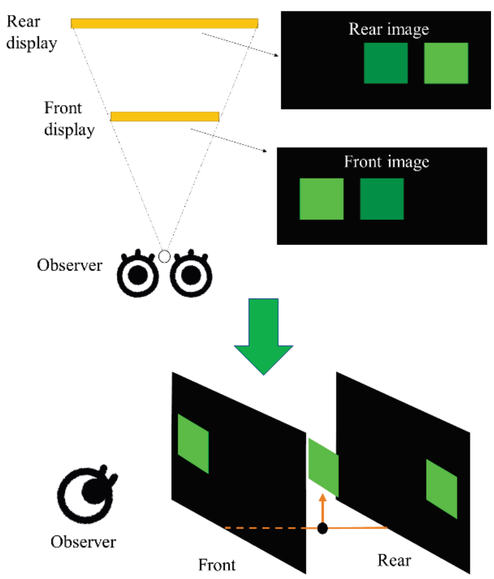

Fig. 3 Conceptual diagram of the DFD display.

We describe the fusion of the front and rear images in DFD in the depth direction and the continuous depth representation by luminance ratio. Figure 4 shows a conventional case in which whole front and rear images are not overlapped. The left side of Fig. 4 shows the arrangement of observation and the right side shows the retinal images in the left and right eyes. Let A and B (C and D) be the edges of the front (rear) image. In conventional case in Fig. 4, the order of the perceived edges at retinal images is the same for both eyes as for the CABD. This makes it easier to perceive the two images before and after as separate objects using binocular disparity.

Figure 5 shows the overlapped case of the whole front and rear images from a single point between the observer's eyes. In overlapped case, the order of the perceived edges is CADB (ACBD) for the left eye (right eye), and the order of the edges is different for the right and left eyes. Therefore, two images are not perceived as two images due to binocular disparity and are perceived as one image.

Left illustration in Fig. 5 shows the luminance distribution of the front and rear images and the retinal images. When a low-pass filter is applied to the luminance distributions, the luminances are represented by curved lines. At such curved lines, the observer is well known to perceive the steepest part of the curve (indicated by the arrow in Fig. 5) as an edge. The edge of the retinal image becomes closer to the edge of the images with the higher luminance images. When the luminance ratio of the front and rear images is changed, the position of this edge changes, resulting in a change in disparity for both eyes. Therefore, continuous depth representation can be achieved simply by continuously changing the luminance ratio.

From this perceptual model, consistency in perceived depth dependence can be guessed at various observation distance with fixed size ratio of front and rear images. When observation distance is decreased, perceived front size ratio increases. Until perceived front size is increased over the situation that above mentioned edge order inversion is lost, depth fusion and depth change may remain.

When observation distance is increased, perceived front size ratio decreases slightly. Since this change in perceived front size ratio does not affect edge order inversion, depth fusion and depth change may remain at increasing observation distance.

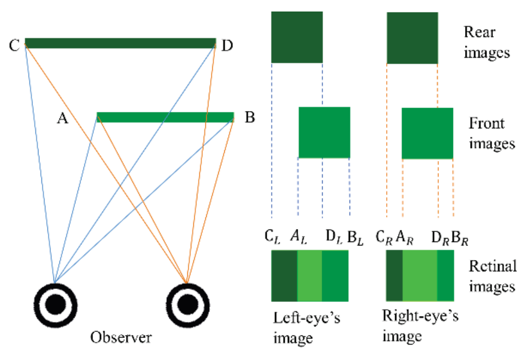

Fig. 4 Perceptual model when the images of the front and rear two planes overlap only partially.

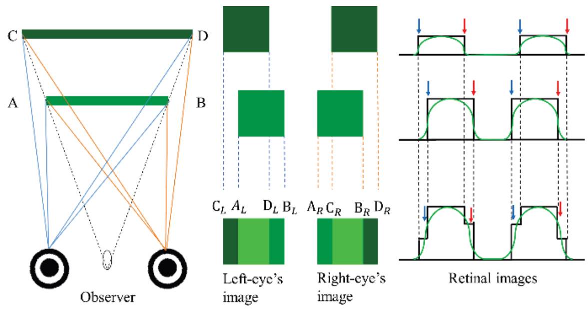

Fig. 5 Perceptual model of superimposed front and rear images from a single point between the observer's two eyes.

3 Experimental Apparatus for Perceived Depth

Diagram of the proposed optical system is shown in Fig. 6. The proposed optical system consists of a display placed behind the aerial image formed by the optical see-through AIRR. The distance relationship for this experiment is shown in Fig. 7. In this experiment, we will confirm that stereoscopic viewing can be performed using the proposed method with a stereo camera. the distance between the planes was 250 mm, the length of one side of the square displayed on the rear display was 38 mm, the length of one side of the square displayed on the front display was 34.96 mm (92% reduction from the square on the rear display), and the appropriate viewing distance from the front display (where the images projected on the front and rear displays completely overlap from the center point of both eyes) was 2875 mm. The observation points in this experiment were 2300 mm from the front display (a distance reduced by 80% from the appropriate observation distance) and 5000 mm from the front display (a distance extended by approximately 174% from the appropriate observation distance). The luminance distribution in pixel values of the front image (aerial image) and the rear image (LCD) is shown in Fig. 8. The displays for the front and rear images are similar. The brightness setting for the rear display was set to 15% and the brightness setting for the display used as the light source for the front display was set to 100%. The horizontal axis is the pixel value to be measured. The vertical axis is the measured luminance value.

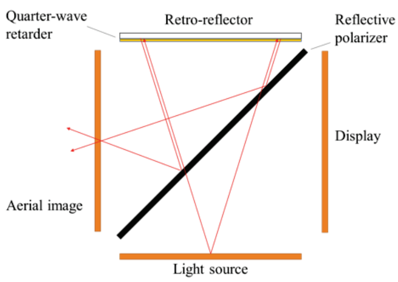

Fig. 6 Structure of DFD display with optical see-through AIRR.

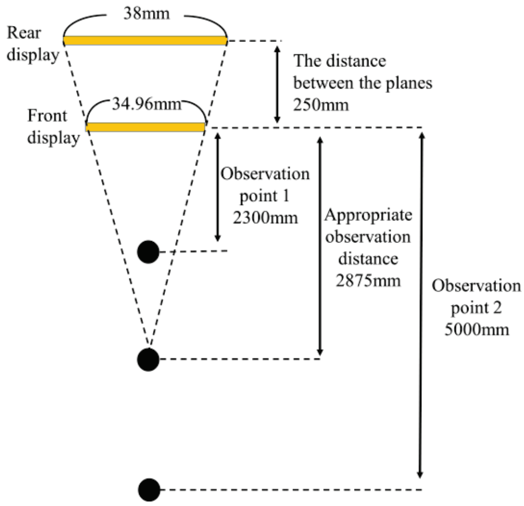

Fig. 7 Geometric arrangements of the rear LCD display and the front aerial display.

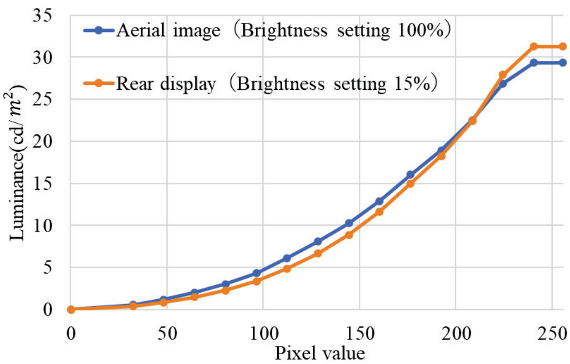

Fig. 8 Relationships between the pixel value and the luminance in the front image (aerial image) and the rear image (LCD).

4 Perceived Depth Dependence at aerial 3D display

Stereoscopic photographs were taken for estimating perceived depth dependences in aerial DFD display at near observation distance of 2300 mm and far observation distance of 5000 mm, in which appropriate observation distance was 2875 mm. Figure 9 shows a LRL (left-, right- and left-eye image) format of stereoscopic image taken at a near distance of 2300 mm from the front display (a distance reduced by 80% from the proper viewing distance). Figure 10 shows a LRL format of stereoscopic image taken at a far distance of 5000 mm from the front display (a distance that extends approximately 174% from the proper viewing distance). Three squares were shown on the displays so that the luminance of the squares were all the same from the observer. The left square displayed a luminance ratio of 100% in the rear, the right square displayed a luminance ratio of 100% in the front, and only the middle square had a varying luminance ratio in the front and rear. Note that a luminance ratio of 100% was approximately 29.3 cd/m^2.

In Figs. 9 and 10, there are five pairs of luminance ratio combinations for the middle square (Front : Rear = 100 : 0, 75 : 25, 50 : 50, 25 : 75, 0 : 100). Figures 9 and 10 show that the 3D image depth change can be successfully observed even when observation distances of 2300 mm and 5000 mm are much different from the appropriate viewing distance.

5 Discussion

Even when observation distances are much different from the appropriate observation distance, perceived image are not separated into two images and can be perceived as a single image. In addition, the image depth can be changed as a 3D image with depth.

By using the proposed optical system, 3D images can be successfully perceived even when the arrangement of front and rear images is not same as overlapped case in Fig. 5. As predicted by the model shown in Fig. 5 and section 2.3, large robustness in observation distance is clarified by using our aerial 3D display composing optical see-through AIRR with DFD display. Our next challenge is to verify how far away (or close) an object can be observed at a certain distance between surfaces and at a certain object size.

6 Conclusions

We proposed a new optical system that forms 3D aerial images using the optical see-through AIRR and DFD display, which are aerial image forming technologies. Furthermore, we clarified that the 3D images can be seen even when the observation distance is forward or backward position from the appropriate distance.

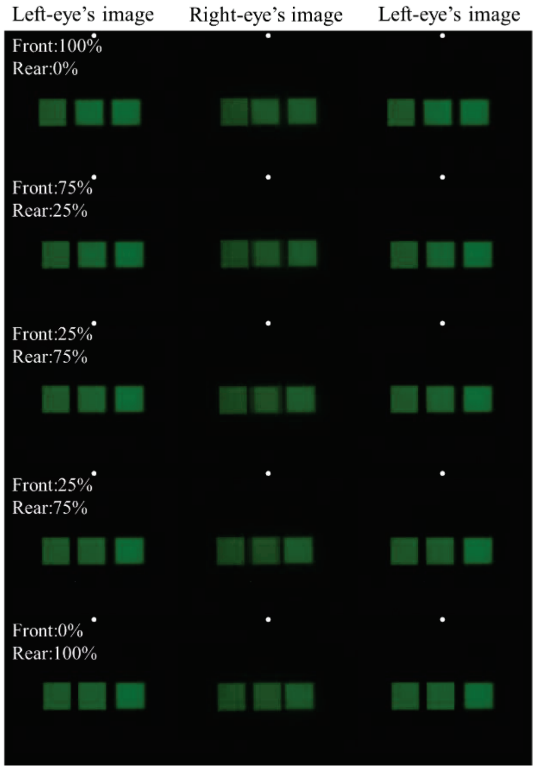

Fig. 9 Stereo image taken at a distance of 2300 mm from the front display. (Photograph taken at observation point 1 in Fig. 7)

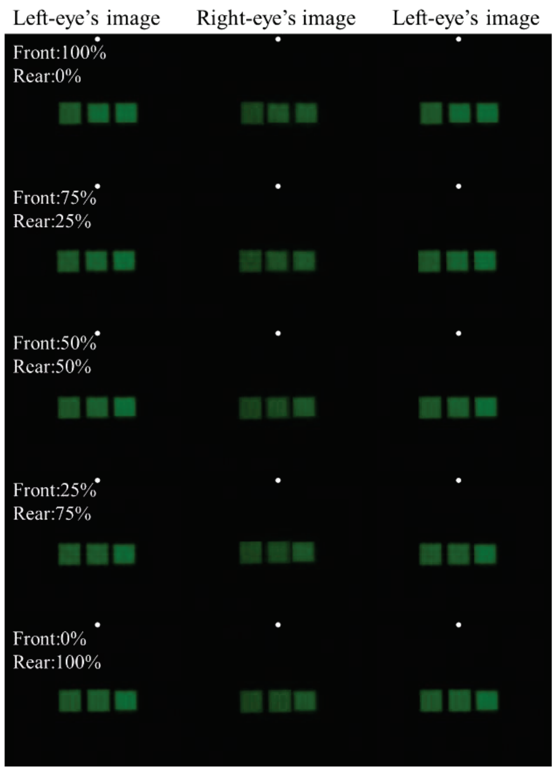

Fig.10 Stereo image taken at a distance of 5000 mm from the front display. (Photograph taken at observation point 2 in Fig. 7.)

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