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Design of Ghost-free Aerial Display by Using Prism and Dihedral Corner Reflector Array

Yuto Osada, and Yue Bao; Graduate School of Integrative Science and Engineering, Tokyo City University; 1-28-1, Tamadutsumi, Setagaya-ku, Tokyo, Japan

Abstract

In a dihedral corner reflector array (DCRA) used as an aerial display, the observer can directly touch aerial images. However, in this optical element, the visibility of the aerial image is reduced by stray light, called a ghost. Although ghost formation can be suppressed using a louver, the viewing angle and brightness of the aerial image also decrease. This paper proposes the design of a ghost-free aerial display using a prism and DCRA. Based on experimental results, the ghost brightness with the proposed method was only about 14% of the DCRA at front. In addition, the aerial image produced by the proposed device was the brightest for 0–20°.

Introduction

With the spread of COVID-19, aerial display appears to be a viable technique for infection control, as it is a non-contact tool [1]. Compared to liquid crystal display (LCD), aerial display is more hygienic, as it can be operated by touching the aerial image directly with combining sensors. A dihedral corner reflector array (DCRA) is an optical system that displays images in air [2]. The optical element displays the image of a light source, such as an LCD in the air. The user can observe an aerial image without wearing a device, such as glasses. However, the ghost image is formed by light that does not contribute to the formation of aerial images. If there is a ghost, the image can be seen at an unintended position, which is confusing. In addition, the visibility of the aerial image is reduced by the ghost when it overlaps [3]. This paper proposes the design of a ghost-free aerial display using a prism and DCRA.

In this study, ASKA3D [2] is used as the DCRA. As shown in Figure 1, the structure has two layers of mirror arrays orthogonal to each other. For example, by reflecting the incident light once in each layer, an aerial image is formed at a plane-symmetrical position with respect to the DCRA. In Figure 1, the mirror surfaces of each layer are arranged in the positive directions of the x- and y-axes. In this case, the incident vectors a and b, which are reflected twice, can be expressed by the following equations [4]:

$$\vec{a} = (a_x, a_y, a_z) \quad (1)$$

$$\vec{b} = (-a_x, -a_y, a_z) \quad (2)$$

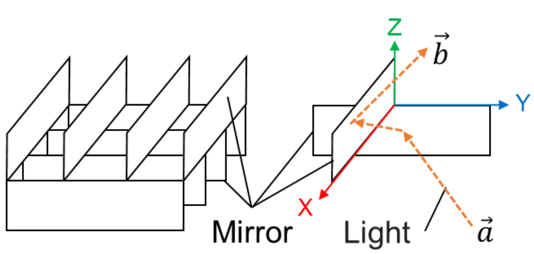


Figure 1. Principle of DCRA

In addition, as shown in Table 1, the image differs depending on the number of reflections in the slit mirror array (SMA) of the DCRA [3].

Table 1. Relationship between image and number of reflections

		SMA_1	
		Odd times	Even times
SMA_2	Odd times	Aerial image	Ghost image
	Even times	Ghost image	Transmitted light

When the light beam emitted from the light source is reflected an odd number of times in each layer, it is focused as an aerial image at a position symmetrical with respect to the DCRA. However, when one layer reflects an odd number of times and the other layer reflects an even number of times, it is a specular reflection, which is called a ghost. Whether it becomes an aerial image or a ghost depends on the angle of incidence of light rays on the DCRA. Therefore, ghost removal is possible by limiting the angle of incidence of light rays on the plate.

Conventional method

Using a louver (viewing angle control film) is a way to remove the ghost while displaying an aerial image. Figure 2 shows the configuration of the ghost-removal method using louvers.

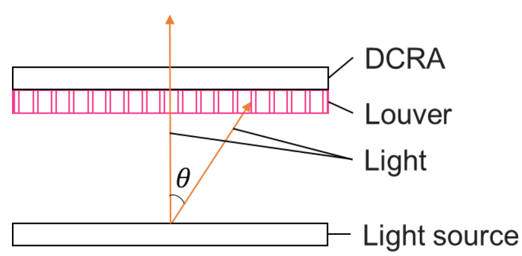


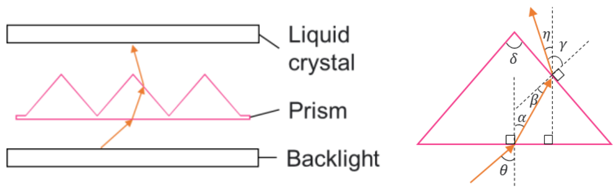
Figure 2. Principle of conventional method

This film can block light rays that form a ghost. According to the patent [5], ghost is removed by limiting the angle of incidence of light to the DCRA. For example, 30° or less is a suitable choice. However, the problem is that the viewing angle of the aerial image is limited, and the brightness is lowered by the film.

There is research on ghost detection using simulation and design of devices that do not display ghosts [6-7]. Moreover, ghost-removal methods with polarization, which can be used only with two-layer orthogonal mirror arrays, have been studied [8]. This is difficult to apply to products such as ASKA3D, because each layer of the mirror array in the plate has a sawtooth cross-section and is UV-cured [3]. Radially arranged DCRAs have also been proposed as a design for ghost-free aerial displays [9]. The viewing angle of this method was theoretically ±90°. However, it can produce a distorted floating image or a large stray light if a large light source is used. To solve this problem, it is necessary to extend the distance between the light source and the DCRA. In this case, space efficiency is reduced, and the aerial image becomes blurred as distances increase [10].

Proposed method

By focusing on light-refraction by prism, we propose the design of a ghost-free aerial display using DCRA. The configuration of the proposed device is illustrated in Fig. 3(a). The state of the light-ray refraction by the prism is shown in Fig. 3(b).



(a) Configuration of the proposed device (b) State of light-ray refraction

Figure 3. Principle of proposed method

In the proposed device, a prism is installed between the liquid crystal and the backlight in LCD, which is the light source of the aerial display. Because light causes refraction at the interface between media with different refractive indices, the light rays forming the ghost can be refracted and imaged as an aerial image by using an appropriate prism. Therefore, it is considered that the brightness of the aerial image is improved compared to that of the conventional device. In the conventional method, light rays with an incidence angle of 30° or more are blocked. Accordingly, the proposed device is designed to have the same viewing angle as a conventional device.

As shown in Figure 3(b), the angle of incidence on the plane side of the prism is θ, the emission angle from the plane side of the prism is α, the angle of incidence on the apex side of the prism is β, the emission angle from the apex side of the prism is γ, and η is the deviation angle of the emitted light from the vertical direction. Let 1 be the refractive index of air, and n be the refractive index of the prism. How much the incident light is refracted and emitted is calculated by the following equation from Snell's law [11].

$$\alpha = arc\sin\frac{\sin\theta}{n} \tag{3}$$

$$\beta = \frac{\pi-\delta}{2} - \alpha \tag{4}$$

$$\gamma = arc\sin(n\sin\beta) \tag{5}$$

$$\eta = \gamma - \frac{\pi-\delta}{2} \tag{6}$$

We calculated the emitted angle by changing the incidence angle of light rays on the prism. We selected a prism whose emitted angle fit within 30° to the left and right.

Simulation of prism

In this study, the optimum apex angle was examined using polymethylmethacrylate resin (PMMA). It is used as an optical material because it has the same transparency and small dispersion as optical glass [12]. The refractive index n_d of PMMA was 1.492 [12]. Figure 4 shows the results of a refraction simulation, in which the apex angle is changed by 10°, from 0° to 170°, and the incident angle is changed by 10°, from 0° to 90°. If the total reflection is caused by the first prism surface, only the case where the light is immediately emitted from the other prism surface is described.

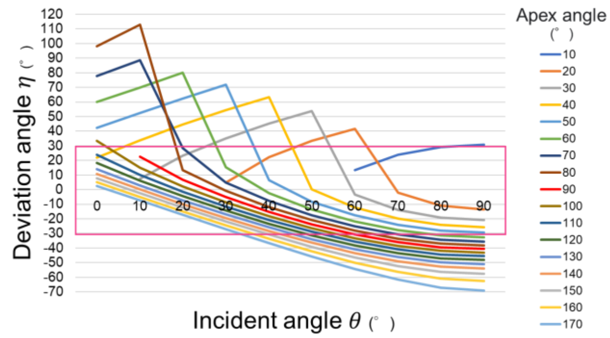


Figure 4. Results of a refraction simulation

When the apex angle is 10° to 80°, it is totally reflected once on the prism surface, and it is out of the range of 30° due to the second refraction on the prism surface. If the apex angle is 100° or more, it is refracted for the first time on the prism surface, but as the incident angle increases, the deviation angle deviates from the range of 30°. When the apex angle is 90°, and the incident angle is small, it is retroreflective and does not emit. However, it fits well in the range of 30° to the left and right compared to other angles. Therefore, it is considered that the best fit among these is when the apex angle is 90°.

Experiment and Result

The brightness of the aerial image and the ghost were measured and compared with the DCRA only and the devices of the conventional method and the proposed method. Figure 5 shows the experimental equipment in the vertical direction.

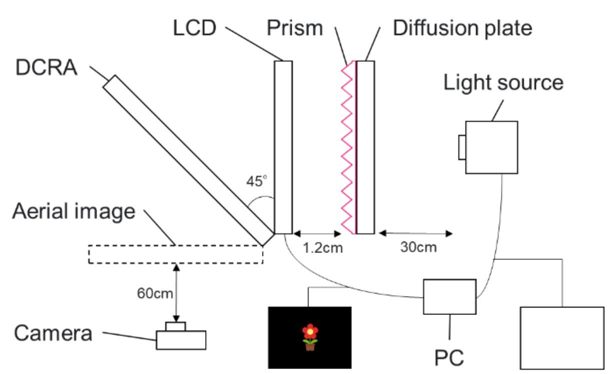


Figure 5. Experimental equipment

The details of the experimental equipment are listed in Tables 2–8. From the simulation results, the prism was made of PMMA with an apex angle of 90°. When a normal prism was used, the thickness increased in proportion to the size of the light source. Therefore, a prism array was used in the experiments. In this case, the louver was selected from the one recommended by Asukanet Co., Ltd.

Table 2. DCRA

Product name	Asukanet ASKA3D
Size	200 × 200 mm from Octagon with opposite side 345 mm
Mirror pitch	0.5 mm

Material	Borosilicate glass

Table 3. Transmissive LCD

Product name	Samsung LT1 220 MT02
Size	22 inch (1680 × 1050 pixel)
Power	DC 12 V/4 A (5 V/1 A during experiment)

Table 4. Prism Array

Product name	SIGMAKOKI LPV-200S-90-0.05
Size	200 mm × 200 mm × 2 mm
Apex angle	90°
Prism pitch	0.05 mm
Material (Refractive index)	PMMA (n_d = 1.492)

Table 5. Diffusion plate

Disassembly source	IBM T221TFT LCD

Table 6. Light source

Product name	BenQ TH682ST projector
Resolution	1920 × 1080 pixel
Brightness	3000 lm

Table 7. Camera

Product name	Samsung Galaxy S10
Number of pixels	About 12 million pixels
ISO sensitivity	320
Exposure time	1/45 s
Aperture value	F2.4

Table 8. Louver (viewing angle control film)

Product name	HIKARI Looknon-N8
Viewing angle	30° left and right
Visible light transmittance	71.2 %
Material	PET

As the louver limit angle is 30° to left and right, the angle formed horizontally from the normal direction of the aerial image was changed by 10°, from 0° to 20° for shooting. The shooting was performed in a dark room. To calculate the brightness of the aerial image and the ghost, the two images were trimmed from the captured image. Trimming was performed based on the position where the aerial image and ghost were displayed using DCRA only. The brightness is the average of the pixel values in one channel of the grayscale image in Equation (7). Equation (7) is used as a grayscale equation based on human color-vision traits [13].

$$Y = 0.299\mathrm{R} + 0.587\mathrm{G} + 0.114\mathrm{B} \quad (7)$$

The captured images of each method are shown in Figures 6–8. The trimmed images are shown in Figures 9–11. Figures 12 and 13 show the brightness-calculation results of the aerial image and that of the ghost, respectively. Figure 12 shows the aerial image of the proposed method is the brightest at any angle. The brightness of the aerial image found with the proposed method is approximately 1.1 times that of the DCRA only method. It is also 1.2 times that of the conventional method at 0°, and 4.3 times at 20°.

Figure 6. Captured images of DCRA only

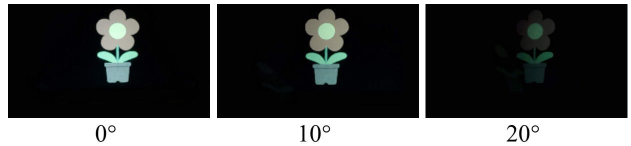


Figure 7. Captured images of conventional device (Louver)

Figure 8. Captured images of proposed device (Prism)

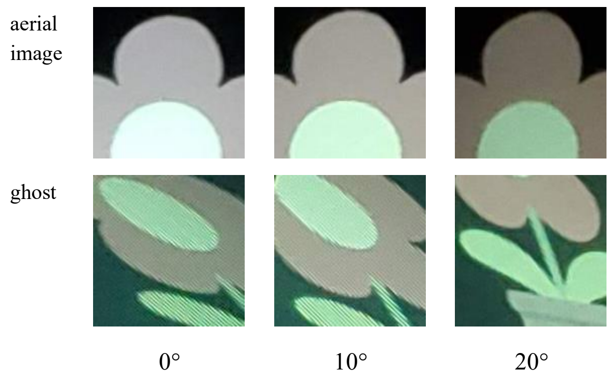


Figure 9. Trimmed images of DCRA only

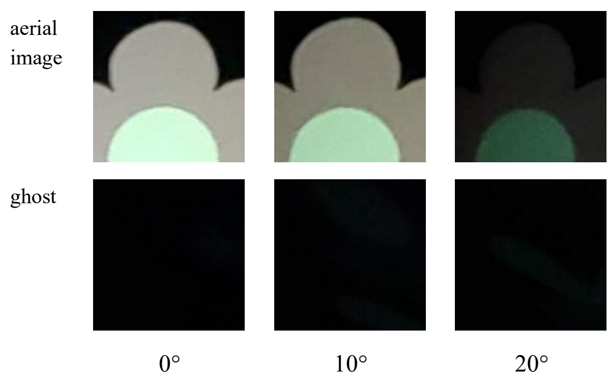


Figure 10. Trimmed images of conventional device (Louver)

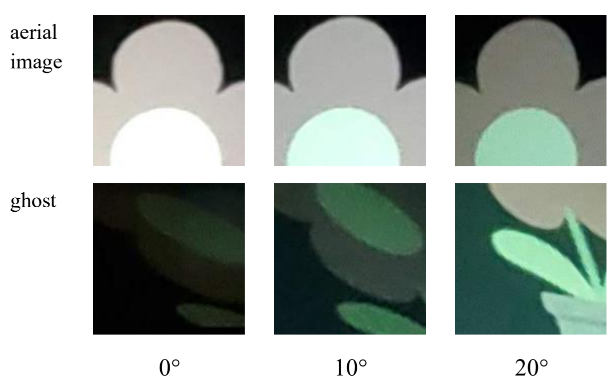


Figure 11. Trimmed images of proposed device (Prism)

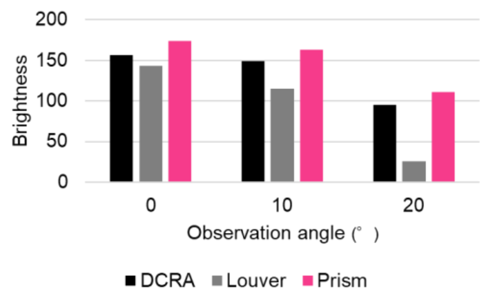


Figure 12. Brightness calculation result of the aerial image

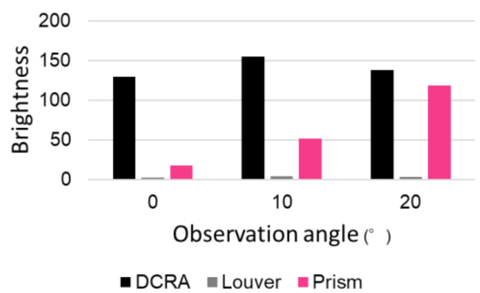


Figure 13. Brightness calculation result of the ghost

It is considered that in the conventional method, the light is blocked by the louver and becomes darker as the angle increases. However, in the proposed method, the light is not blocked, and the brightness does not decrease. On the other hand, from Figure 13, at any angle, the ghost of the proposed method is darker than that of the DCRA only method. However, it is brighter than that of the conventional method. The brightness of the ghost is approximately 0.14 times that of the DCRA only and 9 times that of the conventional method at 0°. However, at 20°, it is approximately 40 times that of the conventional method. We chose a prism with a deviation angle close to 30° by simulation. However, if the angle of incidence is large, the deviation angle does not fit within 30°. Therefore, it is considered that the light rays that are incident, are at 30° or higher form the ghost.

Conclusion

The DCRA has been proposed as an aerial display. However, the visibility of the aerial image is diminished by stray light, referred to here as the ghost. It impedes the formation of the aerial image. A ghost can be removed by limiting the angle of incidence using a louver. However, it decreases the brightness of the aerial image and limits the viewing angle. In this study, the ghost is removed by installing a prism between the liquid crystal and the backlight (light source) to provide display directivity. The experiment with the proposed method led to approximately 14% of the DCRA only ghost-brightness at the front. In addition, the aerial image of the proposed device is the brightest for 0° to 20°. As the light rays forming the ghost were used to form the aerial image, it is considered that the brightness was improved.

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References

[1] Akihiro Tumura, "Illustrated Electronic Devices Now (45) Touch the Virtual Screen in the Air, Non-contact Technology noted by COVID-19", Economist, 98 (36), 82-84 (2020).

[2] Makoto Otsubo, "Display and Non-Contact Input Device Using It", P2019-53749A, JP (2019).

[3] Hirotsugu Yamamoto, "ASKA3D Plate -Plane-symmetric Optical Imaging Element Using Micro-Reflecting Element with Orthogonal Mirror-", Recent Developments and Prospective Applications of Aerial Display, CMC Publishing Co, Ltd, 35-45 (2018).

[4] Kosuke Hiratani, Daisuke Iwai, and Kosuke Sato, "Towards shadowless projection mapping using mid-air image projection by retro-transmissive optical system", The 62nd Annual conference of the Institute of Systems, Control and Information engineers (2018).

[5] Tatsuya Ito, "Aerial Image Display Device", P2019-105744A, JP (2019).

[6] Ayami Hoshi, Shunji Kiuchi, and Naoya Koizumi, "Design a mid-air image system without stray light", The 25th Annual Conference of the Virtual Reality Society of Japan, 2B3-1 (2020).

[7] Sungwon Choi, Sungwoong Park, and Sung-Wook Min, "Design of ghost-free floating 3D display with narrow thickness using offset lens and dihedral corner reflector arrays", Optics Express, 28(10), 15691-15705 (2020).

[8] Tatuya Okawa, Hajime Katsumoto, Hajime Kajita, Naoya Koizumi, and Takeshi Naemura, "Stray light shielding using polarized light in a two-layer retrotransmission optical system", The 21st Annual Conference of the Virtual Reality Society of Japan, 33C-02 (2016).

[9] Yuta Yoshimizu and Eiji Iwase, "Radially arranged dihedral corner reflector array for wide viewing angle of floating image without virtual image", Optics Express, 27(2), 918-927 (2019).

[10] Yui Osato and Naoya Koizumi, "Optical system that forms a mid-air image moving at high speed in the depth direction", IEICE technical report, 118(502), 73-78 (2019).

[11] Mesaki Yoshinori, Sotokawa Akio, Tanaka Akira, Tomatsu Masahiro, Kaiwa Kazumasa, Yuza Hiroaki, and Kato Masayuki, "New Backliting Technologies for Liquid Crystal Display (IV)", ITEJ technical report, 17(48), 33-38 (1993).

[12] Hiromasa Kawai, "Plastic molding materials for precision optics", Optics, 24(2), 69-75 (1995).

[13] Hitoshi Tamura, "Color system and color space", Nippon Institute of Technology, http://www3.nit.ac.jp/~tamura/multimedia/color.html (2009).

Author Biography

Yuto Osada received a Bachelor's degree in computer science engineering from Tokyo City University, Japan, in 2020. He is currently attending the master's course at Tokyo City University. His research interest includes aerial display.

Yue Bao received Ph.D. degree from Kanazawa University, Japan, in 1996. He has been a professor at Tokyo City University since 2004. His research interest includes 3D display, image processing and mobile robot.