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High-Resolution Aerial 3D Display Based on Lens-Enhanced Aerial Imaging by Retro-Reflection (LeAIRR) and Light-Field Display

Kazuaki Takiyama*, **, Toru Iwane*, Shiro Suyama* Hirotsugu Yamamoto*
***Utsunomiya University, Tochigi, Japan**
****JSPS Research Fellowship, Tochigi, Japan**

Abstract

A high-resolution aerial 3D display has been developed using lens-enhanced aerial imaging by retro-reflection (LeAIRR) and light-field display. LeAIRR reduces blurs caused by structures of retro-reflector and improves resolution of the aerial image. The formed high-resolution 3D aerial images have depth information and change depending on the observer's position.

Author Keywords

light-field display; aerial display; 3D images; high resolution; LeAIRR

1. Introduction

Three-dimensional (3D) displays provide depth information compared to two-dimensional (2D) displays, enabling observers to experience spatial information equivalent to the real world [1]. These 3D displays have gained attention for various applications in education, medicine, and entertainment. The light field display forms 3D images by reproducing optical information in a real space with multiple lights from a 2D display [2]. The light-field display has been proposed by use of a 2D-lens array [3], a lenticular lens array [4], and a holographic screen [5] combined with the 2D display. However, the light-field display has problems of difficulty in reproducing deep depths due to a lens focal distance limitation [6, 7]. As a result, its reproducible depth range is restricted to the vicinity of its hardware. For automotive and public applications, a 3D information screen must be formed without any surrounding hardware to prevent accidental contact with the optical system. Such an aerial 3D display allows users to manipulate 3D images in mid-air.

In previous study, an aerial imaging by retro-reflection (AIRR) [8] optical system by the use of the light field display as a light source has been proposed to form 3D images in mid-air away from the optical system [9]. The AIRR optical system consists of a light source display, a beam splitter, and a retro-reflector, and forms aerial images and have a wide viewing angle and scalability. The light from the display is reflected by the beam splitter and retro-reflected by the retro-reflector to form aerial images at a plane-symmetrical position.

The aerial images are significantly blurred compared to the light source display due to ray shift, diffraction, and scattering from the retro-reflector depending on the floating distance [10, 11]. The ray shift refers to the difference in the optical path between the incident light and the retro-reflected light depending on the aperture size of the retro-reflector [12]. Diffraction is caused by the aperture limitation of the retro-reflector and increases as the distance from the retro-reflector to the aerial images increases [13]. Light incident on the retro-reflector that reflects three times within each element becomes retro-reflected light, while the light reflected only once or twice becomes scattered light [14]. In addition, scattering is caused by the edges and manufacturing errors in the retro-reflector.

In a previous report, we proposed a lens-enhanced aerial imaging by retro-reflection (LeAIRR) optical system, which combines the AIRR optical system with a convex lens to achieve the resolution equivalent to a flat-panel display with 441 PPI [15]. In this optical system, the aperture size of the retro-reflector is reduced by the convex lens, and this also reduces ray shift. In addition, the retro-reflected light is focused by the convex lens, which reduces the effects of diffraction and scattering.

The objective of this research is to improve the resolution of 3D aerial images by combining a light-field display and an LeAIRR optical system. The LeAIRR optical system enables the formation of aerial 3D images in mid-air. In the experiment, formed aerial images are captured from the front, left, and right observer directions to show that the aerial images gives parallax and convergence of the reconstructed aerial 3D images.

2. Principle of High-Resolution Aerial 3D Display Based on LeAIRR

The proposed optical system consists of a light-field display, a reflective polarizer, a convex lens, a quarter wave retarder film, and a retro-reflector, as shown in Fig. 1. The corner cube array structure of the retro-reflector is shown in Fig. 2(a). Light incident on the retro-reflective prism is reflected three times inside the element to retro-reflect light, as shown in Fig. 2(b). The convex lens is positioned so that the retro-reflector surface is conjugate to the aerial image plane. The 3D image of the light-field display is a depth-reversed the 3D images, because the aerial images formed by the proposed optical system is depth-reversed at plane symmetrical position. Light from the light-field display is reflected with polarization perpendicular to the transmission axis of the reflective polarizer and is focused by the convex lens, forming a magnified image at the position of the retro-reflector. The light that passes through the λ/4 retarder film becomes circularly polarized and is retro-reflected. The retro-reflected light that passes through the λ/4 retarder film again becomes linearly polarized. The retro-reflected light is converged by the convex lens. The light is transmitted with polarization parallel to the transmission axis of the reflective polarizer and forms 3D aerial images at a plane-symmetric position of the light field-display.

The proposed optical system forms sharper aerial images then does the conventional AIRR optical system, as demonstrated by the images in Fig. 3. In the proposed optical system, the convex lens forms a magnified images of the light source images at the retro-reflector position. The convex lens performs reduced imaging of the corner-cube prisms on the aerial image position. Therefore, the aperture size of the retro-reflector is reduced in the aerial image surface, which reduces the ray shift that depends on the lens magnification. In the proposed optical system, the position of the aerial image is where the convex lens forms the images of the retro-reflector. The diffracted or scattered light by the retro-reflector is collected by the convex lens. The light forms the aerial images which reduces the effects of diffraction spread and scattered light by the retro-reflector.

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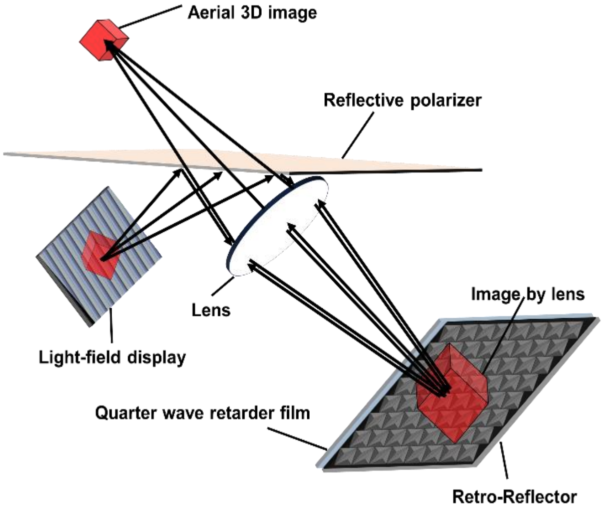
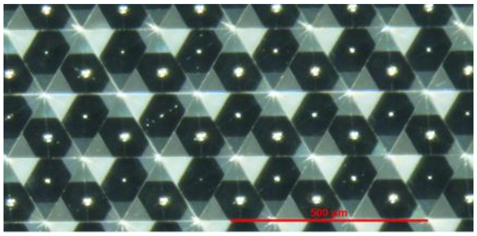
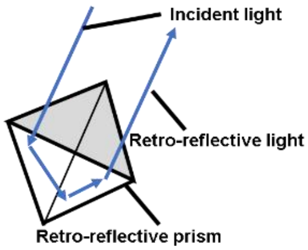


Figure 1. Principle of the high-resolution aerial 3D display based on LeAIRR.



(a) Retro-reflector structure



(b) Light spread by retro-reflector

Figure 2. Characteristics of the retro-reflector.

(a) Aerial image by conventional AIRR

(b) High-resolution aerial image by LeAIRR

Figure 3. Comparison of the 2D aerial images.

The light-field display used in this research reconstructs a horizontal light field. It consists of a lenticular lens array and a flat-panel display. The lenticular lens array covers the flat-panel display as shown in Fig. 4. Unlike the ordinary autostereoscopic displays that generate multiple images for their design viewing positions, the light-field display generates multiple rays that pass through each lenticular lens. Note that the direction of the lenticular lens is slanted with respect to the vertical direction of the flat-panel display to increase density of horizontal rays. The reconstructed light field gives depth cues for viewers, including convergence, binocular parallax, and motion parallax.

The image on the flat-panel display is computed based on rays that pass through the lenticular lens array and reach the 3D object. The ray density is the highest at the lenticular lens array and gradually decreases with increasing distance from it. As a result, the light-field display has a limited reproducible depth range.

To reconstruct a 3D image in mid-air, we use a light-field display as the light-source display in the LeAIRR optical system. As mentioned above, the LeAIRR optical system forms an image of the light-source display in a plane-symmetrical manner with respect to the reflective polarizer. Consequently, the aerial image has a reversed depth compared to the 3D image displayed by the light-field display. To achieve the desired 3D image, the 3D image generated by the light-field display must have its depth reversed accordingly.

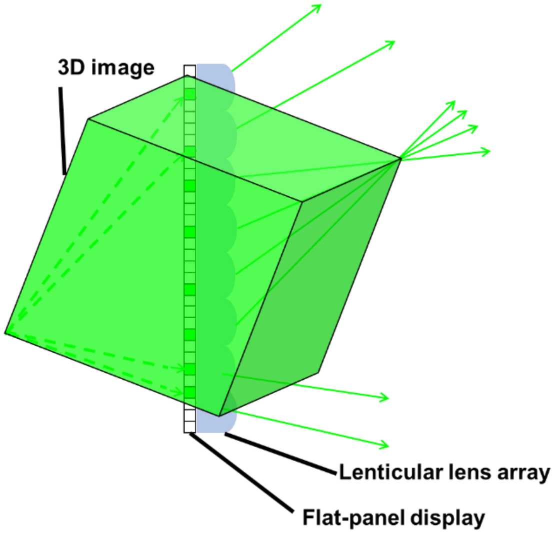


Figure 4. Reconstruction of a 3D image by a light-field display by use of a lenticular lens array.

3. Forming High-Resolution 3D Aerial Images

Experimental Setup

The 3D aerial images of the proposed optical system and the conventional 3D AIRR optical system are compared by changing the camera's viewing direction. A schematic diagram of the experimental setups is shown in Fig. 5. Our optical system consists of a light-field display, a reflective polarizer, a retro-reflector (RF-AC, prism type, Nippon Carbide Industries Inc., Japan) covered with a quarter-wave retarder film, and a convex lens (focal length = 150 mm). The light-field display is composed of a 5.5-inch flat-panel display (4K resolution) and a lenticular lens array. The lenticular lens array has a pitch of 403 µm and a focal length of 750 µm and is positioned at a 10.4-degrees angle to the flat-panel display. The distance from the display to the beam splitter, which corresponds to the floating distance, is 150 mm; from the beam splitter to the convex lens is 75 mm; and from the convex lens to the retro-reflector is 450 mm. The image of the light source by the lens is magnified by a factor of 2 at the position of the retro-reflector.

In the experiments, as shown in Fig. 6, the light-field display was placed horizontally, and the reflective polarizer was positioned above the light-field display at 45-degrees from the horizontal plane. A digital camera (D5500, Nikon Corp., Japan) was used to capture the 3D aerial images. The distance from the 3D aerial image to the camera was 1000 mm. The images were captured by using a lens of which focal length was 70 mm with F-number of 5. To confirm that the parallax of the formed aerial 3D image, the camera was positioned directly in front of the 3D aerial image, then 100 mm to the left and the right.

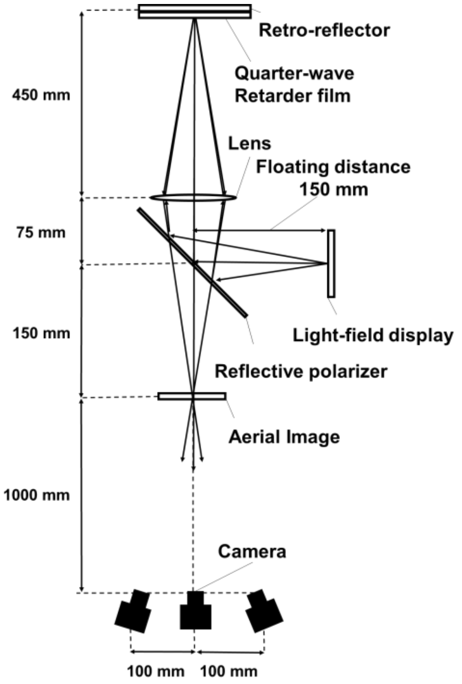


Figure 5. Schematic diagram of the experimental setups.

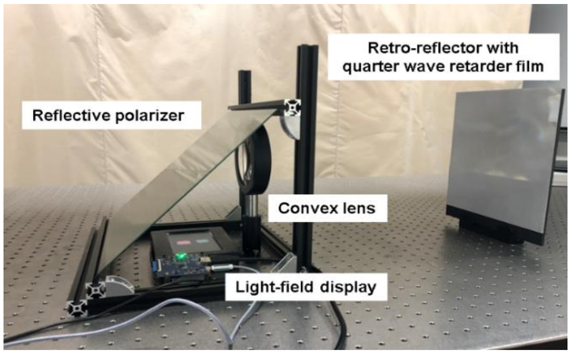


Figure 6. Photograph of the optical system used in the experiments.

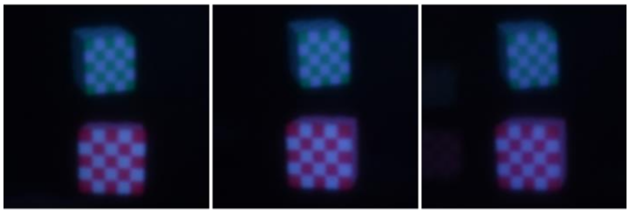
Experimental Result

The photographs of aerial 3D images are shown in Fig. 7 and Fig. 8. The 3D aerial images formed by the LeAIRR optical system show higher resolution than the conventional AIRR optical system. Note that the conventional AIRR optical system here is the same optical system as shown in Fig. 5 without the convex lens. The viewed results of an aerial computer-generated 3D doll, shown in Fig. 8, reveals difference in textures. The proposed optical system shows hairs and clothing in detail.

The photographs of aerial images by moving the camera to the left and the right show the image switching compared to the frontal image. This indicates that the 3D image is formed by the light field display. The 3D aerial images of cube surfaces are seen differently in Fig. 7. The orientation of the displayed 3D aerial images of the character appears to change in Fig. 8.


Left 100 mm Center Right 100 mm

(a) 3D aerial images by proposed LeAIRR optical system


Left 100 mm Center Right 100 mm

(b) 3D aerial images by Conventional AIRR optical system

Figure 7. 3D aerial images of cubes.


Left 100 mm Center Right 100 mm

(a) 3D aerial images by proposed LeAIRR optical system


Left 100 mm Center Right 100 mm

(b) 3D aerial images by conventional AIRR optical system

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Figure 8. 3D aerial images of a computer-graphics doll.

4. Discussion

High-resolution 3D aerial images were formed by the proposed optical system as mentioned above. However, the viewing angle and the size of the aerial image are limited by the numerical aperture and the size of the convex lens in the LeAIRR optical system. Increasing the size of the convex lens made of glass is expensive and heavy. Therefore, we consider that it is necessary to use Fresnel lenses or plastic lenses to increase the size of the proposed optical system. The resolution of the light-field display varies depending on the pitch of the lenticular lens array. If more resolution is required, the lenticular lens pitch in the light field display must be reduced.

Figures 7 and 8 show that the proposed optical system improves the resolution of the 3D aerial images, however quantitative evaluation of the resolution is unavailable from these images. The resolution of the aerial display was measured using line-based modulation transfer function measurements [16]. There is research to measure the resolution of 3D displays by use of Mikelson contrast [17]. In the proposed optical system, it is necessary to measure the resolution based on the components of both light-field displays and aerial displays.

5. Conclusion

We have developed a high-resolution aerial 3D display based on the LeAIRR optical system and the light-field display. The 3D aerial image formed by the proposed optical system has a higher resolution than that of the conventional AIRR optical system. Experimental results show that the formed aerial images give convergence, binocular parallax and motion parallax.

The proposed high-resolution aerial 3D display can used in a wider range of applications as an aerial user interface for displaying fine 3D images in mid-air.

6. Acknowledgements

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7. References

1. Geng J. Three-dimensional display technologies. Advances in optics and photonics. 2013; 5.4: 456-535.
2. Levoy M, Hanrahan P. Light field rendering. Seminal Graphics Papers: Pushing the Boundaries, 2023; 2: 441-452.
3. Okaichi N, Kawakita M, Sasaki H, Watanabe H, Mishina T. High-quality direct-view display combining multiple integral 3D images. Journal of the Society for Information Display, 2019; 27(1): 41-52.
4. Li D, Zang D, Qiao X, Wang L, Zhang M. 3D synthesis and crosstalk reduction for lenticular autostereoscopic displays. Journal of Display Technology, 2015; 11(11): 939-946.
5. Yamaguchi M, Full-parallax holographic light-field 3-D displays and interactive 3-D touch. Proceedings of the IEEE, 2017; 105(5): 947-959.
6. Martínez-Cuenca R, Saavedra G, Pons A, Javidi B, Martinez-Corral M. Facet braiding: A fundamental problem in integral imaging. Opt. Lett. 2007; 32(9): 1078–1080.
7. Yang S, Sang X, Yu X, Gao X, Yan B. Analysis of the depth of field for integral imaging with consideration of facet braiding. Appl. Opt. 2018; 57(7): 1534–1540.
9. Iwane T, Nakajima M, Yamamoto H. Light-field display combined with aerial imaging by retro-reflection. Proc. Imaging and Applied Optics Congress 3D OSA 2016; 2016: TM3A.3.
8. Yamamoto H, Tomiyama Y, Suyama S. Floating aerial LED signage based on aerial imaging by retro-reflection (AIRR). Opt. Express. 2014; 22:26919–26924.
9. Iwane T, Nakajima M, Yamamoto H. Light-field display combined with aerial imaging by retro-reflection. Proc. Imaging and Applied Optics Congress 3D OSA 2016; 2016: TM3A.3.
10. Takiyama K, Yasugi M, Suyama S, Masaoka K, Yamamoto H. Line-Based Modulation Transfer Function Measurement of Aerial Display by Use of Arrayed Optical Elements. SID Symposium Digest of Technical Papers. 2023; 54-1: 109-112.
11. Kakinuma R, Kawagishi N, Yasugi M, Yamamoto H. Influence of incident angle, anisotropy, and floating distance on aerial imaging resolution. OSA Continuum. 2021: 4(3); 865-878.
12. Chipman R A, Shamir J, Caulfield H J, Zhou Q B. Wavefront correcting properties of corner-cube arrays. Applied optics. 1988; 27(15): 3203-3209.
13. Tan Y, Chen H. Diffraction of transmission light through triangular apertures in array of retro-reflective microprisms. Applied Optics. 2012; 51(16): 3403-3409.
14. Chen J, Zhou Y, Hou J, Jiang M, Li Y, He H. Resolution improvement in aerial imaging by a retroreflector using micro aperture arrays. Applied Optics. 2024; 63(3): 636-644.
15. Takiyama K, Iwane T, Suyama S, Masaoka K, Yamamoto H. High-Resolution Aerial Imaging Without Aberration Using a Lens to Reduce Diffraction and Ray Shift by a Retro-Reflector. Proceeding of the international display workshop. 2024; 31: 356-359.
16. Masaoka K. Line-based modulation transfer function measurement of pixelated displays. IEEE Access. 2020; 8: 196351-196362.
17. Lee T H, Jeong Y J. Spatial resolution measurement method for 3D displays from contrast modulation. Virtual Reality. 2024; 28(3): 130.