High-Resolution Aerial Image by Placing a Ball Lens at a Virtually Conjugate Position in AIRR Optical System

Kazuaki Takiyama¹, Shiro Suyama¹, Kenichiro Masaoka²,3, Hirotsugu Yamamoto¹

hirotsugu@yamamotolab.science
¹Utsunomiya University, Yoto 7-1-2, Utsunomiya City, Tochigi 321-0904, Japan
²NHK Foundation, Kinuta 1-10-11, Setagaya, Tokyo 157-0073, Japan
³NHK Science & Technology Research Laboratories, Kinuta 1-10-11, Setagaya, Tokyo, 157-8510, Japan

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ABSTRACT

We propose an aerial imaging by retro-reflection (AIRR) optical system to form high-resolution aerial images by placing a ball lens at a virtually conjugate position. The ball lens parallelizes the incident light on the retro-reflector. The modulation transfer function (MTF) of the proposed optical system is greatly improved.

1 Introduction

An aerial display forms mid-air images that can be seen without the need for special glasses. The passive optical elements of the aerial display form images in mid-air by collecting light from the flat-panel display screen. However, the aerial images are significantly blurred compared to those on the flat-panel display due to ray shift and diffraction from the passive optical elements, depending on the floating distance [1].

In the previous study, we proposed a method to form sharp aerial images in aerial imaging by retro-reflection (AIRR) optics [2, 3]. The typical AIRR optical system consists of a flat-panel display, a beam splitter, and a retro-reflector. The light from the display is reflected by the beam splitter and retro-reflected by the retro-reflector to form aerial images with a wide viewing angle. The optical system proposed in the previous study has succeeded in forming sharp aerial images by placing two ball lenses conjugated between the light source (flat-panel display) and the beam splitter and between the beam splitter and the aerial images in the AIRR optical system, respectively. In this optical system, the light rays are quasi-parallelized by the ball lenses to reduce the blurring of the aerial images due to the ray shifts. However, this optical system is not suitable for practical use because it requires strict alignment of the two ball lenses at the conjugate positions.

We have proposed a method of forming aerial images using a conjugate system without the need for strict alignment [4]. This optical system has a ball lens placed between the beam splitter and the retro-reflector (the virtually conjugate position) in the AIRR optical system. In this optical system, a clear aerial image was formed as in the optical system using two ball lenses.

In this study, we compare the spatial resolution characteristics of aerial images in the proposed AIRR optical system and conventional AIRR optical system. We use the modulation transfer function (MTF) as a measure of the spatial resolution characteristics of an aerial display. The MTF is measured by the line-based MTF measurement method [5].

2 Principles of AIRR Optical Systems

2.1 Resolution Improvement by Parallel Light Incidence

In conventional AIRR, as shown in Fig. 1(a), light rays incident on the retro-reflector are shifted (distance between incident and reflected light) depending on the size of the prism in the element. Consequently, the ray converging points do not coincide. These ray shifts blur the aerial image. Use of ball lenses solves this ray shift problem, as shown in Fig. 1(b). The light rays are collimated by a ball lens. Although the ray shift amount occurs after retro-reflection, the light rays are collimated and form an image at the lens’s focal length, forming a sharp aerial image.

Fig. 1 Principle of improving the resolution of aerial images.

(a) Factors is blurred of aerial images due to differences in the ray shift amount in a retro-reflector
(b) Matching the point of formation of an aerial image by parallel light incidence on a retro-reflector
2.2 AIRR Optical System With Two Ball Lenses at the Conjugate Positions

The principal diagram of the AIRR optical system with two ball lenses at conjugate positions is shown in Fig. 2. The light emitted from the light source is collimated by the ball lens 1, reflected by the beam splitter, and impinges the retro-reflector. The retro-reflected light passes through the beam splitter and is refracted by the ball lens 2 to form an aerial image at a position that is plane-symmetrical to the light source.

2.3 AIRR Optical System With a Single Ball Lens at a Virtually Conjugate Position

The principle of the AIRR optical system with a single ball lens placed between the beam splitter and the retro-reflector (the virtually conjugate position) is shown in Fig. 3. The light emitted from the light source is reflected by the beam splitter and incidents the ball lens. The light refracted by the ball lens is retro-reflected and refracted again by the ball lens. If the light is ideally retro-reflected, the optical path overlaps, making the AIRR optical system with the single ball lens a conjugate system. This optical system does not require the strict alignment that is important for the AIRR optical system with two ball lenses. When the distance from the light source to the ball lens is at the near-axis focal length, the light becomes quasi-parallel as shown in Fig. 3. However, when the distance is longer than the near-axis focal length, the light rays become convergent rays.

3 Experiments

3.1 Setup

The optical system used in the experiments consists of a flat panel display (Blackmagic design: Blackmagic Video Assist 5" 12G HDR: 441 ppi), beam splitter (half mirror), a prism-type retro-reflector (Nippon Carbide Industries: RF-Ax) and ball lens (diameter of 80 mm) in Fig. 4. The distance from the beam splitter to the ball lens was 75 mm.

The MTF was measured by the line-based MTF measurement method. A light measuring device (LMD) (Basler: aca720-520 um) and an imaging lens (Kowa: LM50JC10M) were used to capture an aerial image. A v(λ) filter was attached to the lens. The pixel ratio between the LMD and the display was 2.4. In the experiment, a 1-pixel wide line image was shown on the display.
3.2 MTF Changes With the Floating Distance

To clarify the dependence of the MTF upon the floating distance, MTF measurements were performed by changing the floating distance \( d = 50 \text{ mm} \) and \( 200 \text{ mm} \) in the experimental optical system shown in Fig. 4. The distance \( f \) from the beam splitter to the retro-reflector was kept constant at 150 mm. The retro-reflector was tilted at \( \alpha = 5 \text{ deg.} \) to avoid detecting the light reflected on the retro-reflector surface. The floating distance value was selected for use of aerial buttons (50 mm) and aerial touch panels (200 mm).

The measured MTF is shown in Fig. 5. The MTF at the 50 mm floating distance was improved compared to that of the normal AIRR. However, there was no improvement in MTF at the 200 mm floating distance.

3.3 MTF Changes With the Distance From the Beam Splitter to the Retro-Reflector

To clarify the dependence of the MTF upon the distance from the beam splitter to the retro-reflector, MTF measurements were performed at distances \( f = 150 \text{ mm}, 200 \text{ mm}, 240 \text{ mm}, \) and \( 300 \text{ mm} \) from the beam splitter to the retro-reflector in the experimental optical system shown in Fig. 4. The floating distance was kept constant at \( d = 50 \text{ mm} \). The retro-reflector was tilted at \( \alpha = 5 \text{ deg.} \)

The measured MTF is shown in Fig. 6. The MTF varied with the distance from the beam splitter to the retro-reflector and was greatly improved at \( f = 200 \text{ mm} \) and \( 240 \text{ mm} \) compared to the conventional AIRR.

3.4 MTF Changes With the Angle of the Retro-Reflector

In order to clarify the dependence of the MTF upon the angle of the retro-reflector, the MTF was measured with the angle of retro-reflectors \( \alpha = 5 \text{ deg.}, 15 \text{ deg.}, 30 \text{ deg.}, \) and \( 45 \text{ deg.} \) in the experimental optical system shown in Fig. 4. The minimum angle of the retro-reflector was not 0 deg. in order to avoid detecting the light reflected on the retro-reflector surface. The floating distance \( d \) was kept constant at 50 mm. The distance from the beam splitter to the retro-reflector was set to \( f = 240 \text{ mm} \), which gave the maximum MTF in the experimental results of 3.3.

The measured MTF is shown in Fig. 7. The MTF decreased as the angle of the retro-reflector increased. In the proposed optical system, the MTF was higher than that of the conventional AIRR even when the angle of the retro-reflector was 45 degrees.
4 Discussion

We discuss the factors that caused improvement in the MTF in the proposed AIRR system based on experimental results.

Fig. 5 shows that the MTF was improved when the floating distance was 50 mm, while no improvement was observed at a floating distance of 200 mm. The near-axis focal length of the ball lens used in this experiment can be obtained by the following equation:

$$EFL = \frac{a d}{4(n-1)} \quad (1)$$

When the refractive index of acrylic is 1.49, the focal length of the ball lens is 60.8 mm. In the experiment, the distance from the light source to the ball lens was longer than the near-axis focal length, and it is considered that sufficient MTF improvement was not achieved. Even with a floating distance of 50 mm, the light rays are not collimated but converged because they are far from the near-axis focal length. However, in our previous study [2], the MTF improvement was confirmed even when the distance from the light source to the ball lens was longer than the near-axis focal length. A long floating distance reduces the possibility of accidentally touching the optical elements when operating the aerial display. In addition, the aerial image formed at a long floating distance is easy for the observer to see and operate the aerial screen. Therefore, using a lens with a longer focal length than the near-axis focal length of the ball lens used in this study is expected to improve the MTF even at a floating distance of 200 mm or longer, where no improvement in MTF was observed in this study.

Fig. 6 shows that the MTF improves significantly at $f = 200$ mm and 240 mm. In the conventional AIRR, as the distance from the beam splitter to the retro-reflector increases, the MTF decreases due to the effect of diffraction spread [6]. However, the experimental results show that the MTF improves significantly at $f = 200$ mm and 240 mm, not at $f = 150$ mm, which is the shortest distance when a ball lens is placed. This differs from the conventional MTF decrease due to diffraction spreading. The area of the retro-reflector where the rays enter the lens is considered to change depending on the distance from the ball lens to the retro-reflector since the rays converge because they are far from the near-axis focal length. One of our future works is to clarify the principle of this MTF improvement by a detailed investigation of the dependence of the MTF upon the beam spread and the effective aperture size of the retro-reflector.

Fig. 7 shows that the MTF decreases as the angle of the retro-reflector increases. Because the effect of diffraction spreading increases as the angle of the retro-reflector increases. MTF of the proposed AIRR system shows that even when the retro-reflector is tilted as much as 45 degrees, the MTF is improved compared to the conventional AIRR system.

5 Conclusion

We have proposed an AIRR optical system with a ball lens at the virtually conjugate position. The proposed AIRR optical system greatly improves the MTF compared to the conventional AIRR optical system. This enables us to solve the problem of the high degree of difficulty in the optical design in conventional optical systems due to the placement of two ball lenses at conjugate positions.

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References


