Distant Aerial Image Presentation Using Two Separate Rays of Binocular Parallax Images

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Keywords: aerial imaging, binocular parallax, augmented reality, stereoscopic, distant presentation

ABSTRACT

Aerial imaging displays attract considerable interest. However, their use is hindered by limited presentation area just in front of the optical element. We propose a method for presentation of aerial images at a distance using binocular parallax images formed by two collimated light rays and seen by each eye separately.

1 INTRODUCTION

Unlike conventional flat displays with limited areas, aerial imaging displays can present three-dimensional floating images without a screen, which renders them extremely promising. Existing aerial imaging displays are mainly divided into two types; wearable and stationary. The former allows the user to see the virtual object of computer graphics superimposed on the real world by wearing goggles or glasses with special optical elements, which could be developed as personal devices [1]. As suggested by its name, the latter includes a heavy-duty device and presents aerial images, which can be viewed by multiple people [2]. Some of them realize richer interaction using an advanced sensing technology [3]. In this paper, we focus on the stationary type.

The studies on conventional stationary aerial imaging displays have been focused on the development of technologies that enable high quality images with wide viewing angles, with wide viewing angles. However, the depth range of their presentations is limited to just before the optical element. For example, crossed-mirror array [4] can present aerial images of an object symmetrically on the element surface, which hinders the presentation at a distance. Using a microlens array presents a problem as the spatial resolution of the aerial image decreases far from the element surface, which reduces the quality of the image [5]. Considering the characteristic of aerial image that do not require a screen, if this problem is overcome and distant presentation is realized, various applications can be realized for use in sports, stage performance, and alerting in the public space.

We propose a method of presentation of aerial image at a distance using two rays from distant light sources, viewed by the left and right eye separately and contributing to binocular parallax. Fig. 1 shows a schematic of the proposed optical system. In this system, each beam from the two distant light sources forms a real image of binocular parallax using a lens system, which can be seen by either the left or right eye (one at a time). The image of each beam is formed at the intersection point, where an aerial image can be seen naturally with a small vergence–accommodation conflict. Although it is viewpoint-dependent for one user and can form only a small image, it is sufficiently effective for the applications described above.

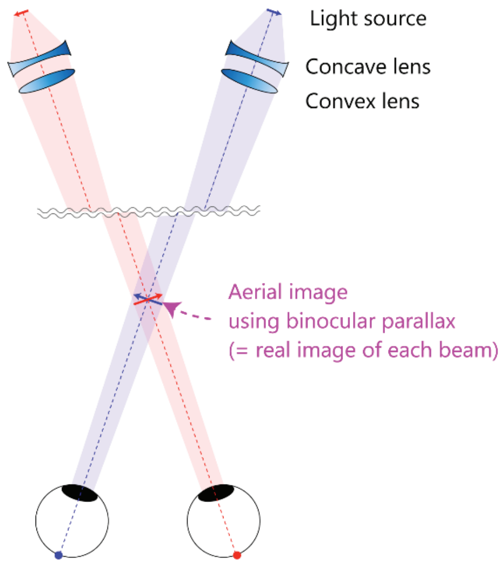

Fig. 1 System overview of distant aerial imaging display using binocular parallax.

In the following section, we explain our method to form an aerial image for a distant user corresponding to his/her various head positions and rotations. Evaluation experiments of the presentation of an aerial image for multiple head positions show the validity of the proposed method.

2 RELATED STUDIES

The most primitive method of presentation of aerial image is that of the real image formed by existing optical elements such as a convex lens or concave mirror, which are used in our method. It can form an image at a distance by appropriately determining the distance between the optical element and object. However, it is challenging to observe the aerial image from two distant eyes simultaneously owing to its narrow aperture. Our method uses real images formed by existing optical elements viewed by the left and right eye, respectively, which overcomes the problem of small aperture size.

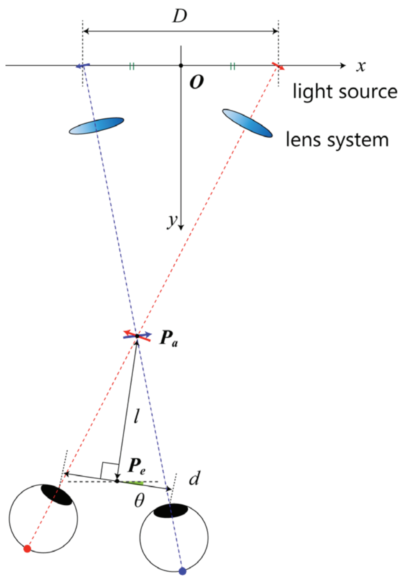

Fig. 2 Asymmetric case of the proposed system and relationship between the parameters that determine the position of the presented aerial image.

Crossed-mirror arrays [4], which often used in recent aerial imaging systems, have simple image formation method (symmetrically to the element plane), which is not suitable for distant usage. Microlens arrays, which can easily form aerial images in front of themselves, have low resolutions for presentation at a distance [5]. A lenticular lens array leads to a large vergence–accommodation conflict when presented at a distance [6], which is also observed in polarized glasses and active shutter glasses. Our method overcomes these problems.

The use of a stationary system using mirror-based scanning or high-intensity laser is also a popular aerial imaging method. Volume-scanning displays realize aerial images by piling up multiple two-dimensional images using a high-speed mirror scanner [7]. However, they are not capable of distant presentation. The method of forming multiple focal points using a high-intensity laser and galvanometer mirror control can form a small aerial image at a relatively long distance [8], as well as our method. However, the risk of hitting a person is inevitable, which is unsuitable for a wide-area use.

3 PROPOSED METHOD

3.1 System Overview

A schematic of the proposed distant aerial image method is shown in Fig. 1. A light ray forming a real image of the light source (display object) is generated by placing a collimating lens system in front of the light source. By designing each ray direction to enter the pupil position of the left or right eye (one at a time), it is possible to present an aerial image at the rays' intersection position. The use of two rays overcomes the narrow aperture of the lens and enables the reliable presentation of an aerial image, regardless of the user's distance from the device and head's rotational angle.

The position of the aerial image is the rays' intersection, as mentioned above, and uniquely determined from the positions of the light sources and the position and rotation of the head. In this section, we formulate it that holds both in the bilaterally symmetrical case (the head is just in front of the device, as shown in Fig. 1) and the asymmetrical case (Fig. 2).

A schematic of our method in the asymmetric case with some parameters is shown in Fig. 2. We denote the coordinate of the user's intereye position as $\boldsymbol{P_e} = (P_{ex}, P_{ey})$, the interocular distance as d, and the rotational angle of the head as θ. The distance between the two light sources is D. The center of the two light sources is assumed to be an original point in the coordinate system. The coordinate of the presented image $\boldsymbol{P_a} = (P_{ax}, P_{ay})$ is expressed by

$$\boldsymbol{P_a} = K \begin{pmatrix} 4P_{ex}P_{ey} - d\sin\theta\,(D + d\cos\theta) \\ 4{P_{ey}}^2 - d^2\sin^2\theta \end{pmatrix} \tag{1}$$

The parameter K is expressed by

$$K = \frac{D}{4\left(DP_{ey} + d\left(P_{ey}\cos\theta - P_{ex}\sin\theta\right)\right)} \tag{2}$$

In particular, when the line consisting both eye positions is parallel to the *x*-axis, where the two light sources are located, the rotational angle of the head $\theta = 0$, and the position of the presented image $\boldsymbol{P_a}$ can be easily obtained by the similarity of the triangles,

$$\boldsymbol{P_a} = \frac{D}{D+d}\boldsymbol{P_e} \tag{3}$$

When the aerial image is presented just in front of both eyes (the distance between the aerial image and each eye is the same), the position of the presented image $\boldsymbol{P_a}$ and its distance from the interocular position l are expressed by

$$\boldsymbol{P_a} = \boldsymbol{P_e} + l(\sin\theta\,, -\cos\theta) \tag{4}$$

and

$$l = \frac{d\left(P_{ey} + \sqrt{{P_{ey}}^2 + D(D\cos\theta + d)\cos\theta\sin^2\theta}\right)}{2(D\cos\theta + d)\cos\theta} \tag{5}$$

respectively. Note that $\boldsymbol{P_e} = (P_{ex}, P_{ey})$ must satisfy

$$P_{ex}\left(l^2\cos^2\theta - \frac{d^2}{4}\sin^2\theta\right) + P_{ey}\left(l^2 + \frac{d^2}{4}\right)\cos\theta\sin\theta = \frac{d^2 l}{4}\sin\theta \tag{6}$$

3.2 Multiple Lens System for Formation of a Real Image at Desired Size and Position.

In addition to the formula for the aerial image's position, it is necessary to appropriately design the lens system so that each ray can form a real image with the same size at the same position $\boldsymbol{P_a}$ regardless the ray's length. In this study, we consider the use of a lens system in which concave and convex lenses are arranged one by one in order from the light incident direction. This is the simplest system that can determine the positional relationship between the two lenses according to desired image magnification and image

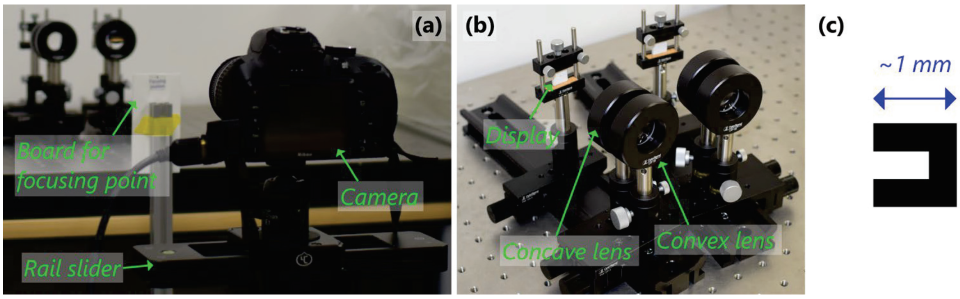

Fig. 4 Appearance of the evaluation experiment. (a) Entire system including an evaluation camera and board indicating the focusing position. (b) Optical system composed of lenses and tiny printed images. (c) Picture used in the tiny printed images.

formation position (notably, a lower limit of the image magnification exists) [9]. According to the formula for the focus length of multiple lenses, the magnification of the real image to the object is smallest at the minimum distance between two lenses.

3.3 Consideration of the Vergence–Accommodation Conflict

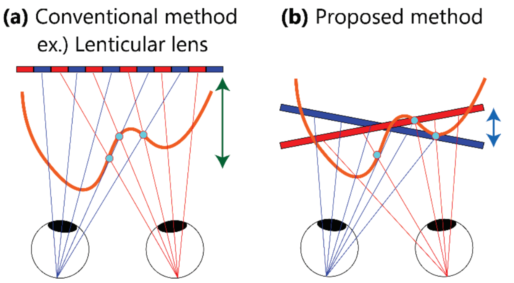

Fig. 3 (a) The conventional method using stereoscopic vision for aerial images has a large vergence–accommodation conflict. (b) Our method has a small vergence–accommodation conflict.

Our method uses stereoscopic vision to form aerial images, which has been used for many technologies, as described in Section 2. However, several of them suffer from a large vergence–accommodation conflict because of the fixed light-emitting surface position, as shown in Fig. 3 (a). In contrast, owing to the imaging lens, our method can place the light-emitting surface at almost the same position as that of the virtual object, as shown in Fig. 3 (b). Therefore, the aerial image can be viewed naturally with little discomfort.

Regarding this content, we only discuss it and do not carry out evaluation experiments.

4 EVALUATION EXPERIMENT

4.1 Experiment Environment

Figs. 4 (a) and (b) shows the overall appearances of the experimental environment and optical system, respectively. A plano-convex lens (focal length: 50 mm) and plano-concave lens (focal length: -70 mm) with a diameter of 25 mm (SIGMAKOKI Co. Ltd.) were used. The minimum distance between two lenses was 25 mm owing to the carriers, which fixed the optical elements. A Nikon D3500 camera was used for the evaluation (camera lens: Nikon AF-S DX NIKKOR 18–55mm f/3.5-5.6G VR (zoom lens, 6000 × 4000 px)). A rail slider was used to imitate both eyes. A board indicating the focusing position of an aerial image was set statically. The interocular distance d was assumed to be 65 mm. An image with a size of approximately 1 mm with 9 pixels, was used as a printed image, as shown in Fig. 4 (c). The position of each lens was calculated using MATLAB to present an aerial image at the desired size and position.

4.2 Experiment Method

By this experiment, we confirmed that the proposed system can show an aerial image according to multiple head positions and angles.

First, we conducted an experiment on the system of using bilaterally symmetry ($\theta = 0°$) for two, near and far, cases ((a) 868.0 mm, (b) 950.0 mm). The distance between the aerial image and intereye position l was 325 mm in both cases. When the distance between the two lenses had the minimum value (25 mm), the distances between the two light sources D were 108.8 and 150.0 mm, while the magnifications were 4.48 and 5.57, respectively. The board indicating the focusing position was set at the crossing position of the two rays. The lenses' positions were properly adjusted with cues of MATLAB calculation and visual feedback. The focal length of the zoom camera was 55 mm.

Second, we performed the same experiment in a bilaterally asymmetric case ((c) $\theta = -14.0°$, $l = 61.1$ mm, $P_{ay} = 471.9$ mm, $D = 236.3$ mm). The magnification was 3.33. The focal length of the zoom camera was 35 mm.

4.3 Results

The experimental results are shown in Fig. 5. When the focus of the camera at each eye's position was adjusted to the depth position where the board was located, the real image was observed at the same position above the arrow indicated by the board. As this is valid for all experimental cases, the two bilaterally symmetrical ones ((a) near and (b) distant) and

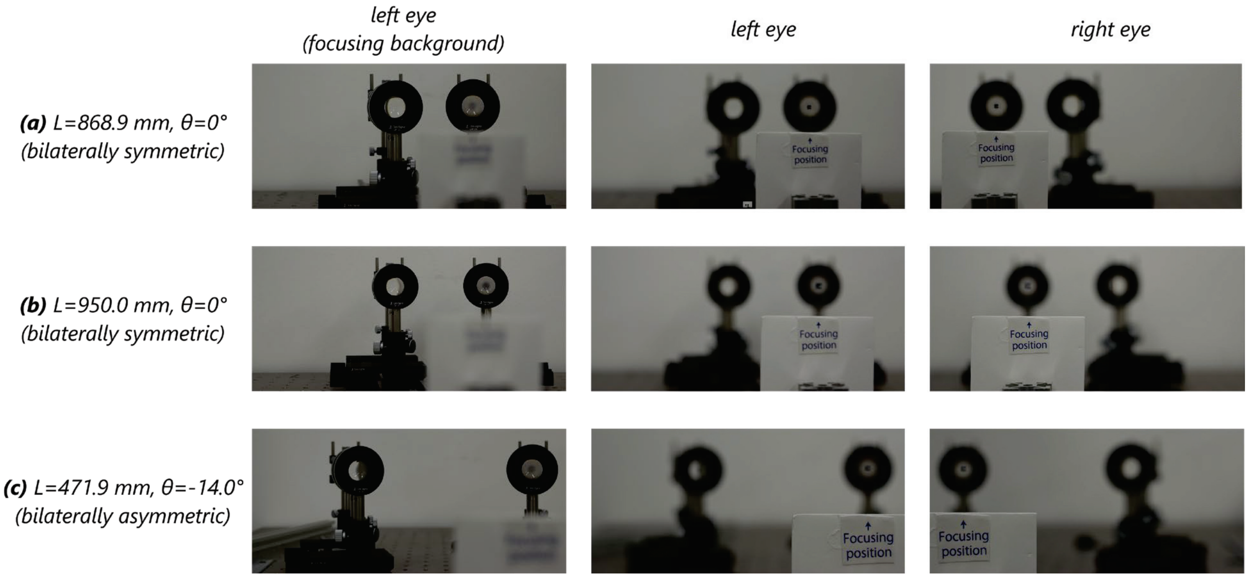

Fig. 5 Results of evaluation experiments of two near and far bilaterally symmetric cases (a), (b) and one bilaterally asymmetric case (c). Note that the focal length of the zoom camera was 55 mm for (a) and (b), and 35 mm for (c).

asymmetric case (c), the proposed method was appropriate. The real image in (b), farthest in the three cases, has a lower brightness than those of the other cases. This could be attributed to the attenuation of light inversely proportional to the squared distance and low light density at the larger magnification in the distant imaging.

5 DISCUSSION

Owing to the configuration of the optical system, the proposed system leads to two main problems, particularly noticeable at a distance. One of them is the limited size of a real image owing to vignetting by the aperture diameter, and the other is that the positional adjustment of the lens system requires a higher resolution of control. These problems can be overcome by selecting lenses with an appropriate aperture diameter and focal length according to the application.

Moreover, in a simple lens system composed of only two lenses, it is challenging to control two factors (imaging size and position) simultaneously because they are interdependent. However, it is possible to overcome this problem using a zoom lens.

6 CONCLUSION

We realized a distant aerial image presentation using two rays, each of which shows a different binocular parallax image observed by the left and right eyes, respectively. Its performances at multiple head positions and angles were analyzed through evaluation experiments. However, a few problems still hinder the real-life application, as described in Section 5, which will be addressed in our future studies.

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