Optical Review (2023) 30:647–656
https://doi.org/10.1007/s10043-023-00844-6

SPECIAL SECTION: REGULAR PAPER

Laser Display and Lighting Conference (LDC' 23), Yokohama, Japan

Method of acquiring shapes using motion capture of aerial images formed by large acrylic panels

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Received: 31 May 2023 / Accepted: 17 October 2023 / Published online: 31 October 2023

Abstract

This study proposes the method of measuring 3D object shapes in an immersive space using a motion capture system. We report on the visualizing the distortion of acrylic panels mounted on a large aerial display and measuring the aberration of the aerial image using a motion capture system. Large aerial displays are made of large acrylic panels, which are subject to distortion due to their own weight. We succeeded in visualizing the shape of the acrylic plate by motion capture and 3D plotting of the positional information. Using a motion capture system, it was found that the aerial image formed by the distorted acrylic plate exhibits astigmatism, which is the difference between the vertical and horizontal focusing position. Furthermore, by drawing the shape of the side surface of the acrylic plate using poster papers, the coordinates were extracted from the imitation paper image, the radius of curvature of the acrylic plate was calculated, and the aberration was calculated. It was found that it is possible to measure the shape in an immersive space using the motion capture.

Keywords Aerial display · Retro-reflection · Motion capture

1 Introduction

In recent years, various applications using cutting-edge technologies are expected in the medical field, such as AI-based diagnosis, surgery using robots, and the use of virtual reality (VR) and augmented reality (AR) technologies for treatment aids and rehabilitation [1]. Aerial displays have the advantage of eliminating the need to wear special equipment (e.g., HMDs), blending easily into the real space without a screen, and reducing the sense of oppression. We expect that the use of aerial displays in patient care will reduce the stress on patients and be useful for diagnosis. For such applications, a large-size aerial display apparatus is needed.

Aerial imaging by retro-reflection (AIRR) has been proposed as a method for forming an aerial image using retro-reflection [2]. AIRR consists of three components: a light source, a beam splitter, and a retro-reflector. The flexibility of the arrangement of components has allowed various studies, such as aerial depth-fused 3D display [3, 4] and omnidirectional aerial display [5]. The AIRR tablet, where the 3D high-speed hand tracking was integrated into the aerial image formed by AIRR, has also been realized to use aerial display as aerial interface [6]. Brightness and resolution of aerial image are issues for AIRR, but methods to solve these issues in terms of software [7] or hardware [8] have also been proposed. Tiling retro-reflective elements have an advantage of allowing the design of a large aerial display. In previous research, we have proposed an immersive life-size aerial display device based on AIRR, which is equipped with motion capture and enables interactive display [9]. The see-through structure of the device provides the observer with the view of the aerial image at the same time as the background [10]. Furthermore, the motion capture enables tracking of the observer's free movements [11–13]. Using this device, we aim to realize rehabilitation for patients with visual field problems due to brain damage by observing their reactions to interactions in which images are projected in an enclosed space, to determine their damaged visual filed, and to recover their visual field function by training them to response to the displayed aerial images. By observing the patient's reaction to the interaction of images displayed in a surrounded space, we can judge the patient's damaged visual

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field and expect recovery of visual field function by training the patient to respond to the displayed aerial image. In such applications, it is important not only to detect the user's position information, but also to measure the 3D position of the aerial image as seen by the user. The use of an acrylic plate as a beam splitter in this device allows the creation of a large and inexpensive device, but the beam splitter is deformed due to its own weight [14]. The deformation of the acrylic plate causes the image formation position of the aerial image to shift, resulting in aberration. This causes distortion in the aerial image produced by the device; however, it is difficult to grasp the degree of its three-dimensional distortion by common measurement tools.

The purpose of this study is to propose the method of 3D position measurement in this device. Using the on-board motion capture system, the shape of the large acrylic plate and the focusing condition of the aerial image at the three-dimensional position are clarified. First, the 3D information of the acrylic panel is obtained by tracing along the acrylic panel with the marker of the motion capture system to determine how the panel is bent. Then, the three-dimensional state of the light collection of the aerial image is obtained. The shape of the acrylic plate is also acquired from the side, and the aberration of the aerial image is calculated to infer whether the 3D positional measurement is correctly performed.

A preliminary result of this study was presented at the 12th Laser Display and Lighting Conference 2023 [15]. In this paper, we measure the acrylic plate and calculate the aberration of the aerial image to compare it with the measured value obtained by motion capture.

2 Principle

Figure 1 shows the principle of see-through AIRR used in this study. In this type, it differs from the conventional AIRR in the arrangement of the retro-reflector. The light emitted from the light source goes to the beam splitter and splits into transmitted light shown by solid lines and reflected light shown by dotted lines. The transmitted light goes to the retro-reflector and is retro-reflected. The light retro-reflected by the retro-reflector goes to the beam splitter and is reflected by the beam splitter to form an aerial image at a position that is plane-symmetrical to the display with respect to the beam splitter. The light first reflected by the beam splitter forms a virtual image. The imaging position of the actual image observed from the front and the virtual image observed from the opposite side is almost the same position. Therefore, the user on the opposite side can also observe the operation that the user in the front performed by on the aerial image.

Large aerial displays have a curved beam splitter, which causes astigmatism in which light emitted from the light source is focused by the beam splitter while shifting in two directions, vertically and horizontally. Figure 2 shows the focusing in two directions. The solid orange line indicates vertical focusing, and the solid blue line indicates horizontal focusing. Vertical condensation is formed at a position that is plane-symmetrical to the acrylic plate and the light source. Horizontal focusing is determined by the circular reflective surface due to the curvature of the acrylic plate. However, if the beam splitter is cylindrical, the horizontal focus is formed based on the principle of reflection by a concave

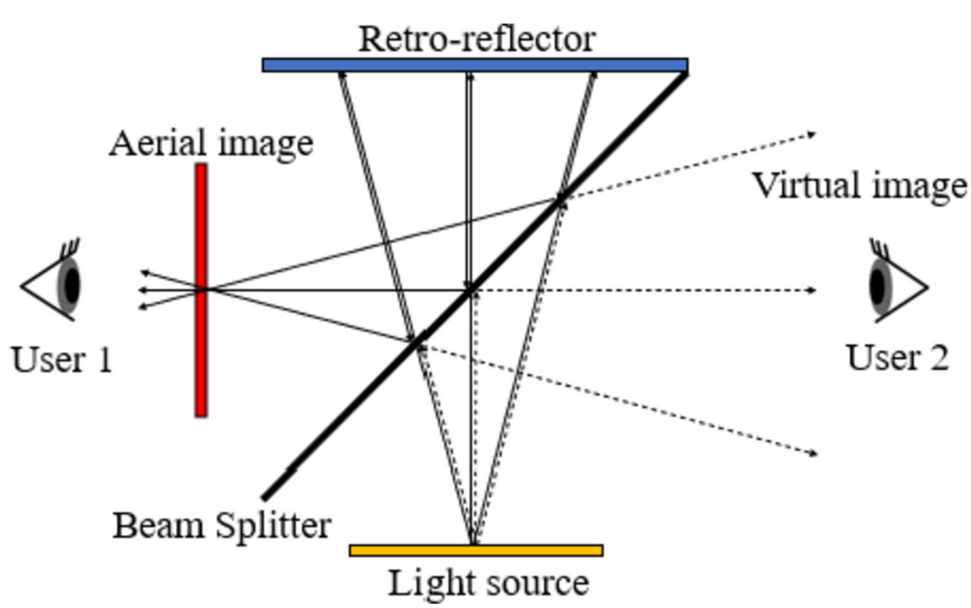


Fig. 1 Structure of optical see-through AIRR

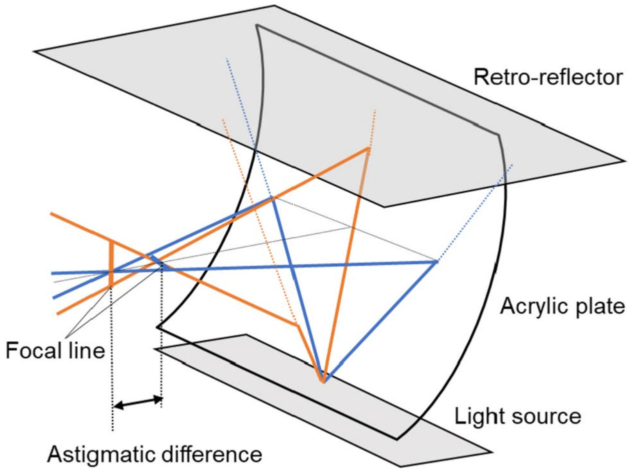


Fig. 2 Aerial image focusing by a large acrylic plate

mirror. Therefore, the focusing of the aerial image when the beam splitter is cylindrical is

$$\frac{-1}{z'} = \frac{1}{Z} - \frac{2}{R}, \tag{1}$$

where Z is the position of the vertical image, Z' is the position of the horizontal image, and R is the radius of curvature.

3 Experiments

3.1 Experimental setup

To obtain 3D positional information of objects in the immersive space, motion capture installed on the device is used. Five camera is installed at eh top of the device, so that the shape of the object in the space can be measured, as shown in Fig. 3. An observer inside the device can obtain the position information of an object to be measured with a marker. We have installed 5 cameras (PrimeX 13 m NaturalPoint, Inc., image resolution of 1280×1240 pixels, 120 frames/s) with infrared emitters that capture movement of a marker held by a user. Figure 4 shows the marker in the experiment. The marker is made of retro-reflector, and the coordinates of the marker can be obtained in 3D position of the camera image. The marker size is 130×110 mm. Figure 5 shows the actual position of cameras and the position of cameras on the software. Figure 6 shows images captured by the five cameras. The acquired information is then plotted in 3D, which allows the visualization even for translucent objects such as acrylic plates, and objects floating in the air such as aerial images.

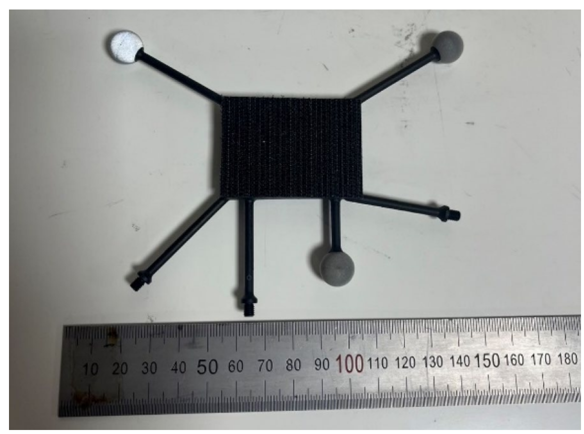
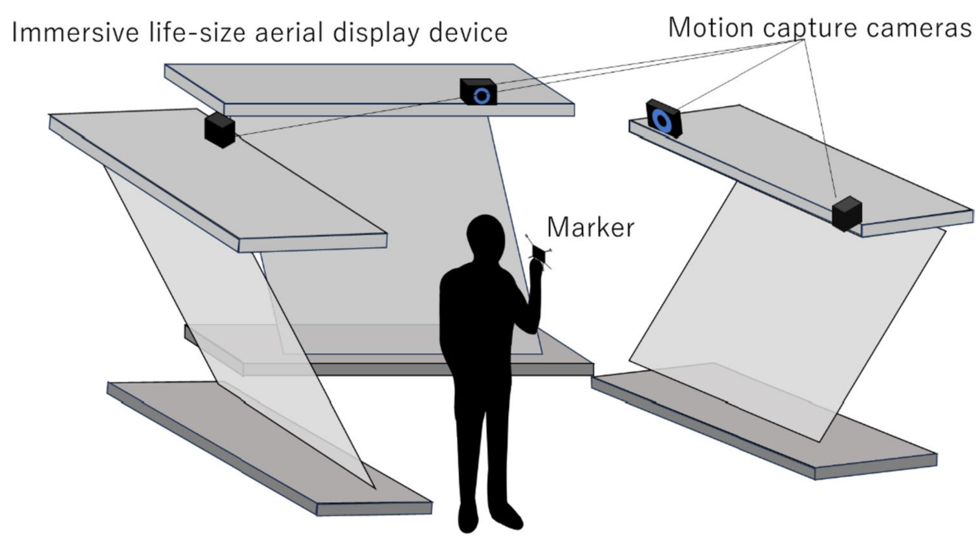


Fig. 4 Photograph of the marker with retro-reflective materials for tracking user movements

Fig. 3 3D measurement on immersive device



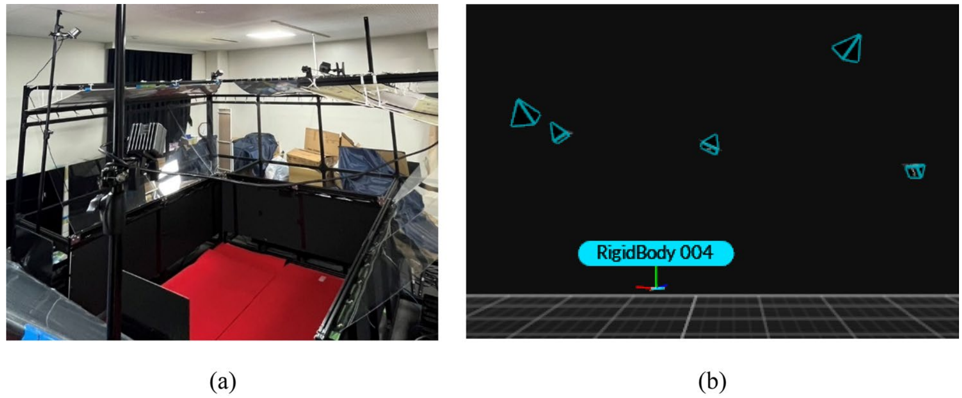


Fig. 5 Motion capture system: **a** The actual position of the cameras installed to capture the marker and **b** the camera positions on the software screen installed to capture the marker

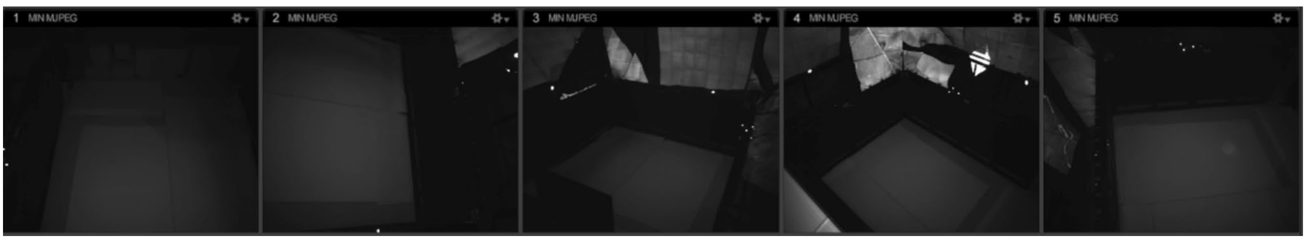


Fig. 6 Images captured by five cameras

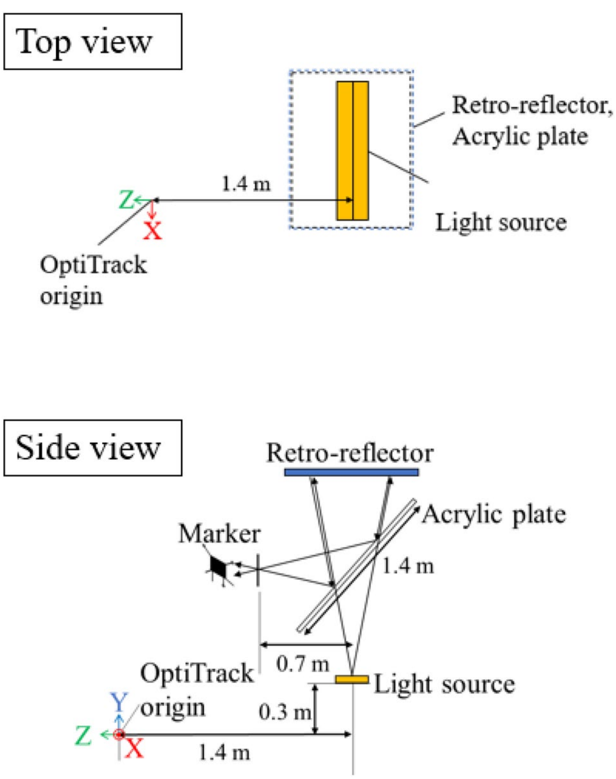


Fig. 7 Composition of a large aerial display with AIRR

Figure 7 shows the composition of a large aerial display using AIRR. The light from the light source follows optical path shown by a solid line and forms an aerial image at plane-symmetric position indicated by a solid line. The LED panel was used as a light source and acrylic plates are used as beam splitter. The axes on the motion capture are X-axis for the direction parallel to the acrylic plate, Y-axis for the direction of height from the ground, and Z-axis for the direction of the acrylic plate.

In a preliminary experiment, we experimented with the precision of the motion capture. The marker was stopped at a certain location for 2 s, and the standard deviation of the coordinate information acquired during that time was acquired were the x, y, z coordinates at the origin of the motion capture and the x, y, z coordinates at a distance of 10 cm. The motion capture update rate was 120 fps, and 240 values were acquired in 2 s. Table 1 shows the experimental results. The standard deviations of all the positional values acquired for 2 s were close to zero, indicating that the accuracy was high enough.

3.2 Measurement of distortion of a large acrylic beam splitter

Figure 8 shows the acrylic plate installed in a large aerial display. This distortion of the acrylic plate surrounded by

Table 1 Standard deviation of acquired coordinates in motion capture

	X		Y		Z	
Measurement position	0 mm	100 mm	0 mm	100 mm	0 mm	100 mm
Standard deviation	0.03339	0.00474	0.01736	0.06850	0.00055	0.00640
	0.04498	0.01366	0.01221	0.01146	0.00069	0.00244
	0.00040	0.00729	0.01288	0.01775	0.00417	0.01259

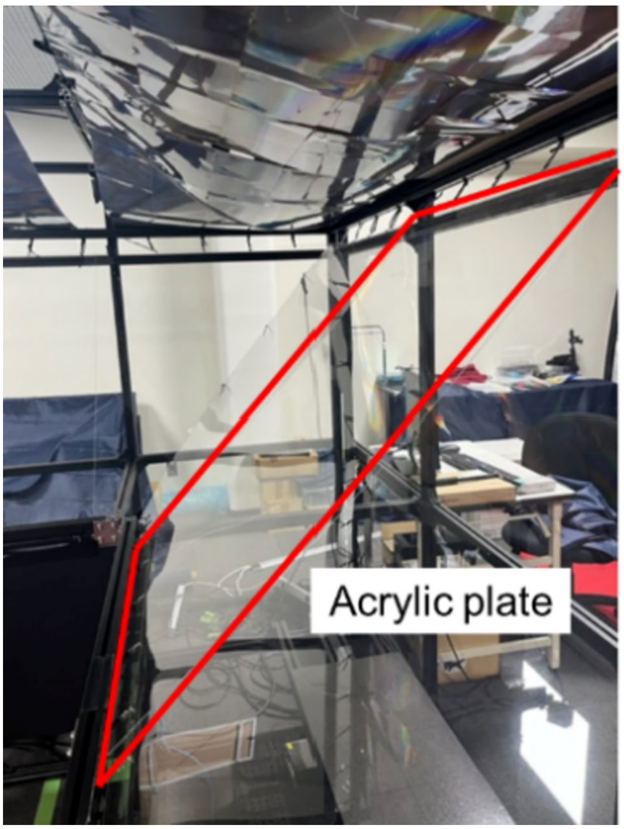


Fig. 8 Photograph of the acrylic plate installed in a large aerial display

red lines is measured. An optical motion capture system, OptiTrack (NaturalPoint, Inc.), is used for the measurement. The observer held the marker and traced the surface of the acrylic plate with the marker to obtain the information of 3D position of the plate. The measurement was conducted three times.

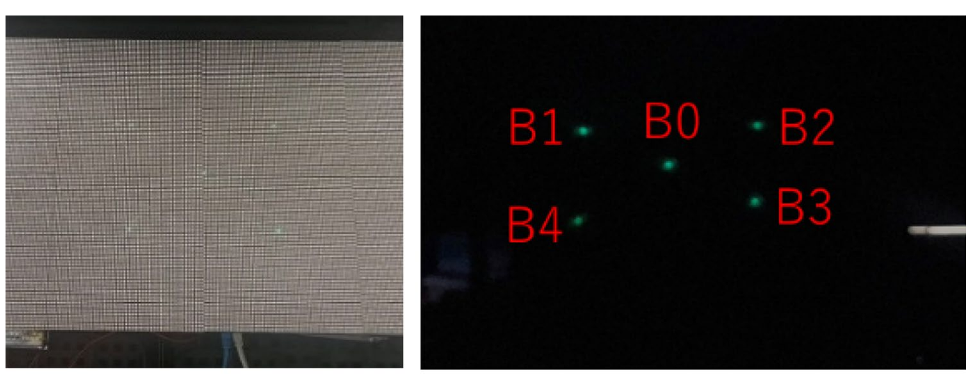
3.3 Measurement of converging light distribution

To measure the 3D distribution of the light that converges to the aerial image a large aerial display, five measurement points (16 × 14 cm) were displayed on the LED panel used for the light source of aerial image, as shown in Fig. 9. Each point was displayed by a single chip on the LED panel. The observer holds the screen and marker, as shown in Fig. 10. The screen was held parallel to the aerial image and moved gradually in the direction of an acrylic plate. The 3D positional information of the focus of the aerial image was obtained by tracing the image on the screen with the tip of the marker each time. The experiment was performed twice for each of the five points.

3.4 Calculation of focusing position of aerial image

Since the large acrylic plate as beam splitter is curved, the vertical and horizontal aberrations can be calculated by approximating the distortion of the acrylic plate to a cylindrical shape. Therefore, it is necessary to acquire position information to approximate the distortion of the acrylic plate to a cylindrical shape. Figure 11 shows when the poster paper is attached to the side of the acrylic plate

Fig. 9 Target pattern: **a** displayed on the light source and **b** displayed aerial image by AIRR



(a) (b)

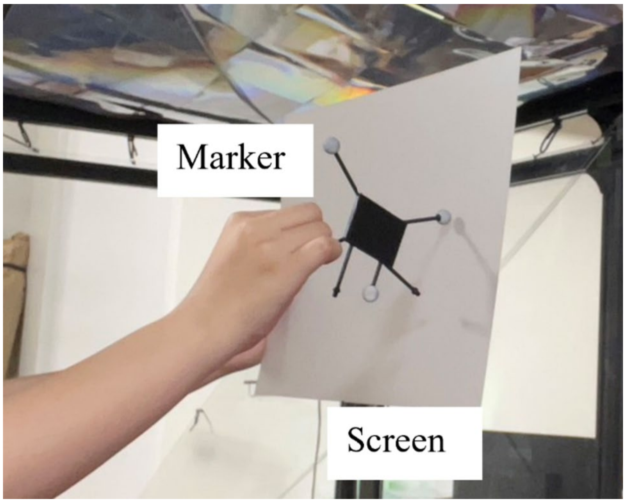


Fig. 10 Photograph of the observer holding the screen and the marker

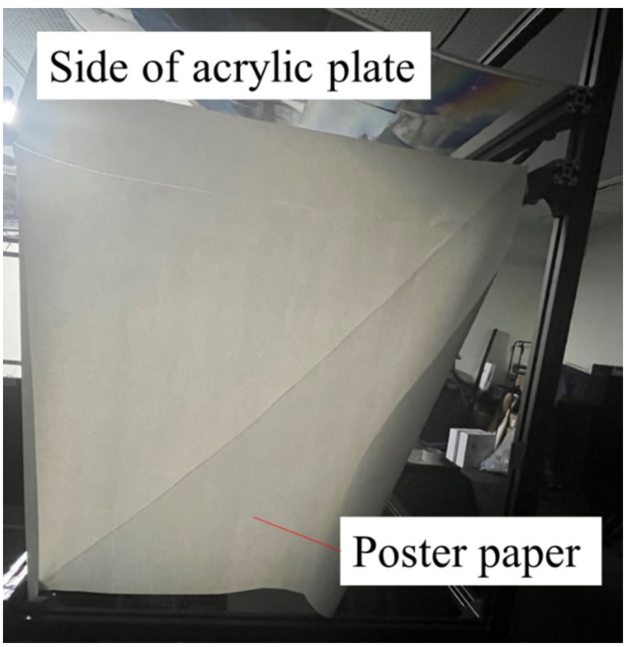


Fig. 11 Photograph of the acrylic plate on poster paper

to obtain distortion information. The distortion of the acrylic plate traced on the poster paper was coordinate acquired on the image. Measurements were taken on both sides of the acrylic plate, and the coordinates of the distortion of the acrylic plate marked on the poster papers were obtained on the image. The ratios of the image coordinates to the actual coordinates were determined from the rulers in the image, and a circle was approximated from these coordinates using the least-squares method. The average of these radius was used as radius of the cylindrical shape of the acrylic plate, and the position of the focus of the aerial image was calculated from the radius of curvature using (1).

4 Results

Figure 12 shows the results of the 3D shape measurement of the distortion of the acrylic plate. From the results of the experiment, it is visualized and revealed that the acrylic plate is distorted.

Figure 13 shows how the aerial image was observed to be focused vertically and horizontally when the screen was moved slightly closer to the acrylic plate. Figure 14 shows the results of acquiring 3D positional information on the focusing of the aerial image caused by the distortion of the acrylic plate. The center of the five displayed points is B0, and the coordinate information of the acquired image is plotted in 3D. It was found that an astigmatism of about 25 cm occurred at B2, the distance between the vertically converged position and the horizontally focus of position. The experimental results show that when the screen was moved toward the acrylic plate (toward the negative direction of the Z-axis on the motion capture system), the light was focused in the vertically (Y-axis) and then horizontally (X-axis) directions.

Figure 15 shows the distortion of the acrylic plate acquired on poster paper. Figure 16 shows the approximated circles on both sides of the acrylic plate. From this figure, when the distortion is approximated as a circle in two dimensions, the radius of curvature is 618 cm on average on both sides. Table 2 shows the aberrations of the aerial image calculated from the aberrations obtained by motion capture and radius of curvature obtained. The calculations are performed on five aerial image aberration measurements obtained by motion capture.

5 Discussion

Based on the standard deviation of the coordinates obtained from the motion capture measurements taken as a preliminary experiment, it is possible to obtain data with an accuracy of ± 0.07 cm at maximum, regardless of the measurement position.

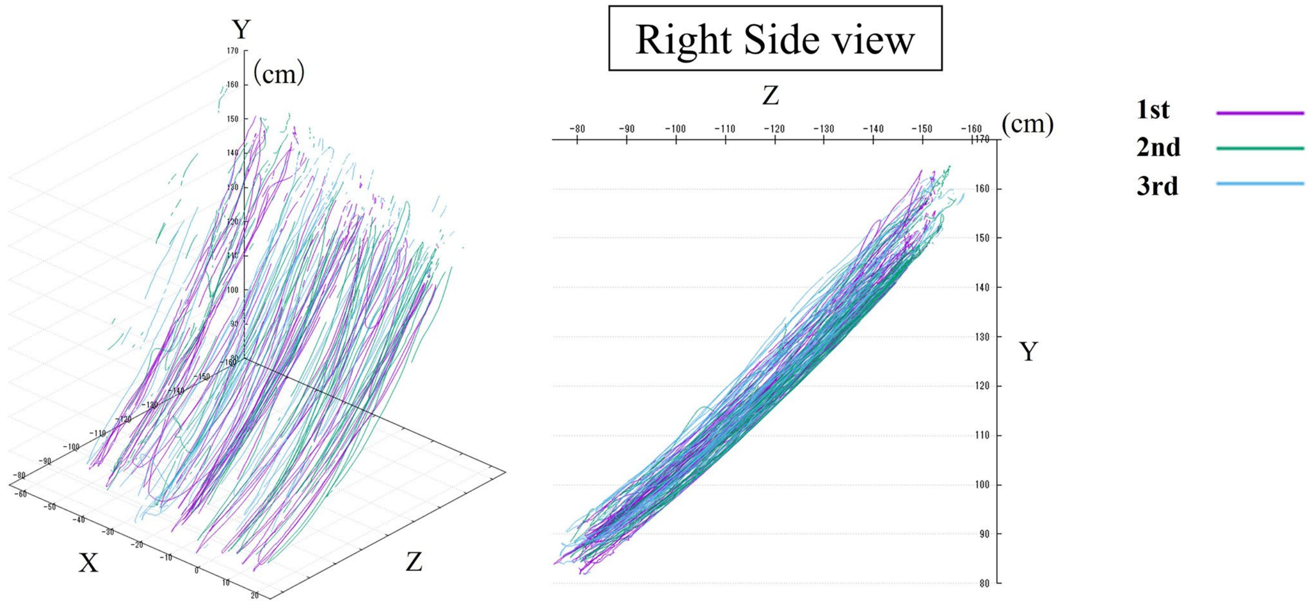


Fig. 12 Measured 3D shape of the acrylic plate acquired by the 3D motion capture system

Fig. 13 Image on the screen: **a** vertically focused light and **b** horizontally focused light

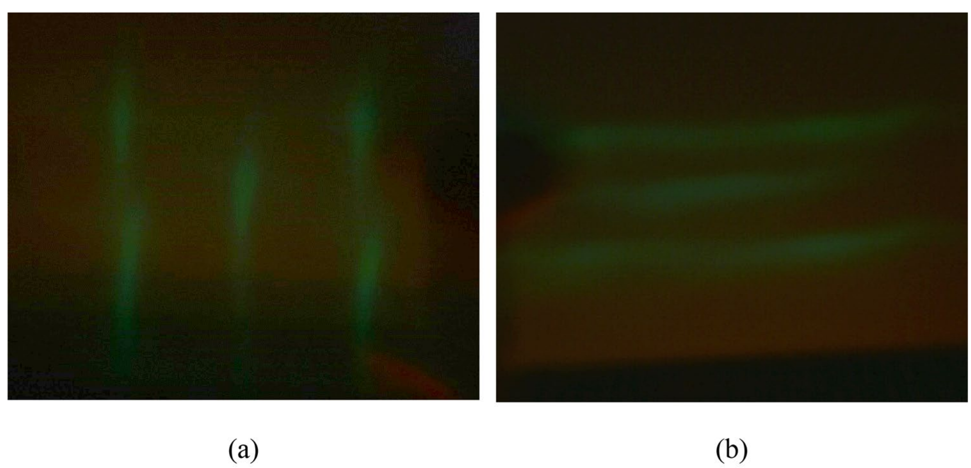


Figure 12 shows that the distortion of the acrylic plate can be visualized by motion capture, and it is clear that differences occur in the Y–Z direction. Table 2 shows that there is a difference between the aberration obtained by motion capture and the calculated aberration. Comparing the measured and theoretical values of aberration, B0, B2, and B4 are nearly in the same plane, but B1 forms an acrylic plane in front, and B3 forms an acrylic plane much further back than the ideal.

In the future study, the measured acrylic plate is approximated to a three-dimensional cylindrical surface and analyzed using ray tracing software. Based on the results of the analysis, it is possible to make corrections from the light source that produces the aerial image.

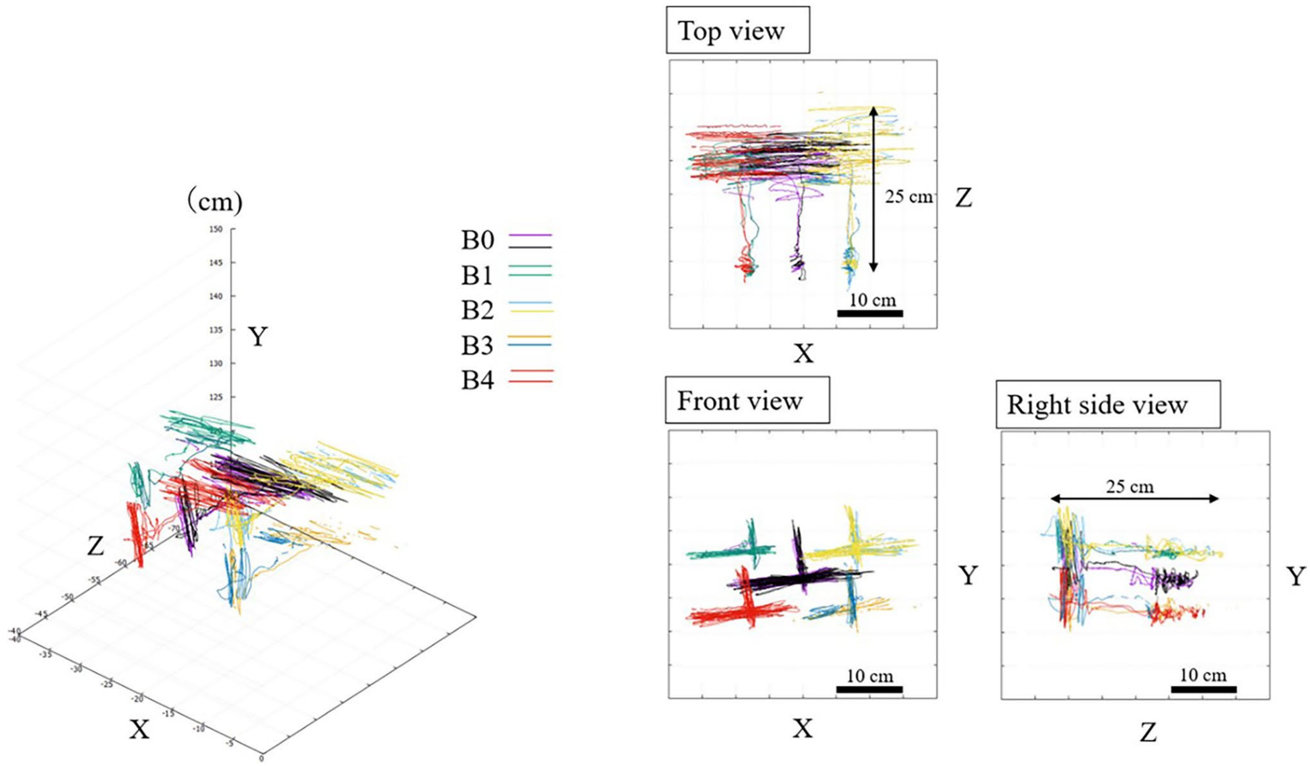


Fig. 14 3D position of the measurement points acquired by the motion capture system

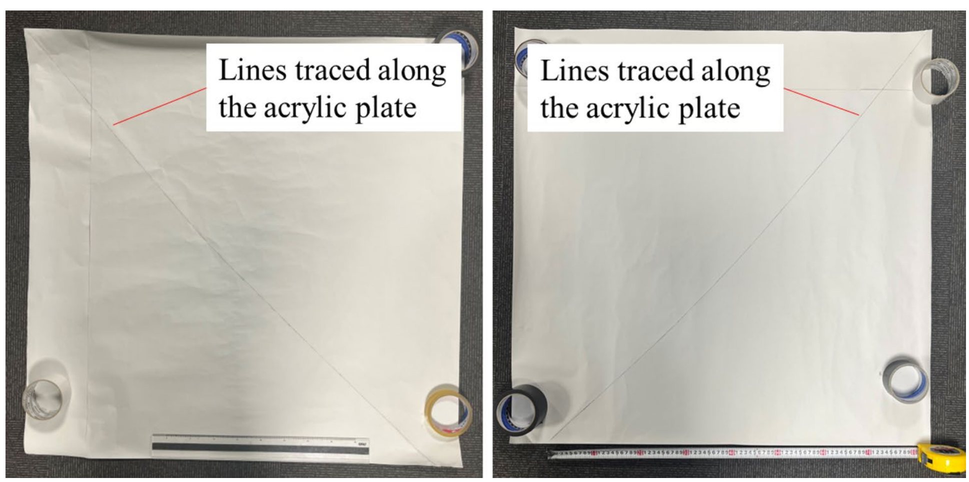


Fig. 15 Photograph of the shape result of acrylic plate drawn on the poster papers

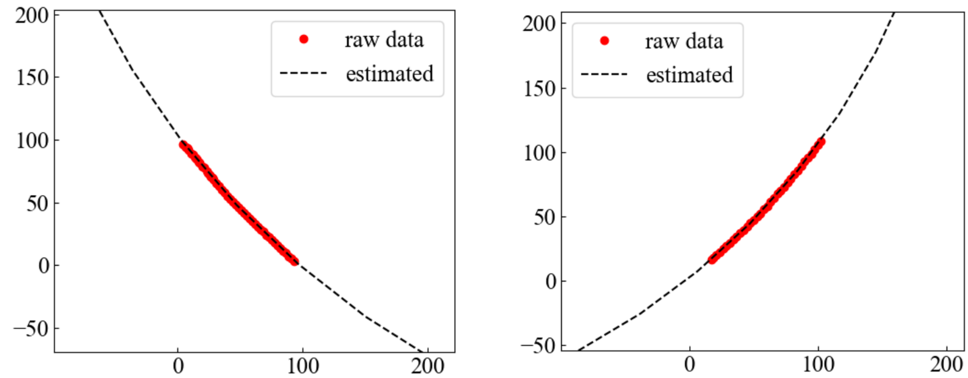


Fig. 16 Circular approximation of acrylic plate

Table 2 Aberrations obtained by motion capture and calculated

Condition name	B0	B1	B2	B3	B4
Aberrations measured by motion capture	216 mm	191 mm	256 mm	274 mm	219 mm
Calculated aberrations	203 mm	232 mm	232 mm	183 mm	183 mm

6 Conclusion

In this study, we visualized the distortion of the acrylic plate installed in a large aerial display and clarified the focusing of the aerial image and the shape of the acrylic plate. A 3D plot of the acrylic plate shape shows that the acrylic plate is not uniformly cylindrical, but is shifted in the Y–Z direction in the motion capture image. The focusing of the aerial image revealed astigmatism, which is a difference between the vertical focusing position and the horizontal focusing position. The aberration was calculated by assuming the acrylic plate to be a uniform cylindrical shape by drawing the shape of the side surfaces of the acrylic plate using poster paper. Comparing the aberrations obtained by motion capture with the calculated aberrations indicated that the acrylic plate was not uniformly distorted.

Author contributions M.A. contributed for this paper as 1st author. She developed the experimental system and conducted the experiments and wrote the original draft. M.Y. and S.S. designed the experimental system and edited the manuscript. H.Y. designed the experiments and edited the manuscript.

Funding A part of this work was supported by JSPS KAKENHI (19H04155, 20H05702).

Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of interest The authors declare no conflicts of interest associated with this manuscript.

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