High-quality direct-view display combining multiple integral 3D images

Naoto Okaichi | Masahiro Kawakita | Hisayuki Sasaki | Hayato Watanabe | Tomoyuki Mishina

Abstract
This paper proposes a method for combining multiple integral three-dimensional (3D) images using direct-view displays to obtain high-quality results. A multi-image combining optical system (MICOS) is used to enlarge and combine multiple integral 3D images without gaps. An optical design with a simple lens configuration that does not require a diffuser plate prevents the deterioration in resolution resulting from lens arrangement errors and the diffuser plate. An experiment was performed to compare a previously developed method with the proposed method, and the latter showed a significant improvement in image quality. A method for expanding the effective viewing angle of the proposed optical design was also developed, and its effectiveness was confirmed experimentally. A prototype device of the proposed optical design was constructed using a high-density organic light-emitting diode (OLED) panel with 8K resolution and 1058 ppi pixel density to achieve 311 (H) × 175 (V) elemental images, a viewing angle of 20.6° in both the horizontal and vertical directions, and a display size of 9.1 in. In addition, the proposed optical design enabled making device considerably thinner, ie, with a thickness of only 47 mm.

KEYWORDS
direct-view display, display system, integral imaging, integral photography, multi-image combination, three-dimensional display

1 | INTRODUCTION

Many studies have been conducted on the autostereoscopic imaging system on the basis of integral photography since it was first proposed1–9 by Lippmann in 1908. With this system, viewers can watch integral three-dimensional (3D) images without special glasses, such that a natural 3D image is presented according to the viewing position. Therefore, the integral 3D imaging system is expected to be a practical 3D imaging system in the future. A common method for displaying integral 3D images is to reconstruct images corresponding to multiple viewpoints by using a lens array with many micro lenses. A projector or a direct-view display, such as a liquid crystal display (LCD) or an organic light-emitting diode (OLED) display, is used as the display device. Elemental images, which include information on light rays from various directions, are input to the display device, and the integral 3D image is

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reconstructed with the lens array. Because the integral 3D system needs to reconstruct a very large number of viewpoint images, a display device capable of displaying an extremely large number of pixels is required in order to improve the quality of the 3D image. Because it is difficult to produce display elements that far exceed the 8K resolution, improving the quality of integral 3D images remains challenging. Therefore, research is actively pursued for improving the quality of integral 3D images by using a combination of multiple display devices.

Many research groups have used projectors as display devices to realize integral 3D imaging systems with multiple display devices. For example, Liao et al. proposed combining multiple images by using multiple projectors and mirrors to increase the pixel count of the integral 3D images. Kawakita et al. used 200 projectors to construct a 3D display system with a 200-in display size and motion parallax exclusively in the horizontal direction. By using a projector, it is possible to change the display size flexibly, such that this system is suitable for displaying a 3D image with a large display size. However, because projectors require a certain projection distance, the overall depth of the apparatus becomes large. For home-use 3D display apparatuses in the future, a direct-view display, such as an LCD or OLED, would be better. Several methods have been proposed to enhance the resolution or expand the viewing zone of the integral 3D image by using multiple display panels and a beam splitter. With these methods, however, a beam splitter that is larger than the size of the display panel must be arranged diagonally between multiple display panels, considerably increasing the size of the whole apparatus.

Previously, a method for increasing the pixel count of integral 3D images that used multiple direct-view displays and a multi-image combining optical system (MICOS) was proposed. Multiple images are combined by enlarging each image with a MICOS, and the gaps between the displays are thus eliminated. Using four displays in the prototype device increased the pixel count of integral 3D images by a factor of 5.66 relative to the device with one display. However, the image quality of the integral 3D image was significantly deteriorated by the MICOSs. Therefore, this study investigated an optical design for combining integral 3D images to produce high-quality results. In order to verify the improvement in image quality, display devices with the previous and proposed optical designs were comparatively evaluated. A method to expand the effective viewing angle of the proposed optical design was also devised and verified experimentally. Finally, a device was constructed using the proposed optical design and a display with high pixel density to combine integral 3D images and produce high-quality results. The results demonstrated that the reconstructed 3D image naturally changed according to the viewing position.

2 | INTEGRAL 3D DISPLAY SYSTEM USING MULTIPLE DIRECT-VIEW PANELS

2.1 | Proposed optical design

The proposed optical design is shown in Figure 1. As illustrated in Figure 1A, lens arrays are placed in front of each direct-view display arranged side by side. The lens array is placed at a position away from the display surface based on the focal length of the elemental lens. Thereby, the divided integral 3D image is reconstructed at each lens array plane. As shown in Figure 1B, the MICOSs

![FIGURE 1](image-url)
are placed in front of the lens arrays, and each of the divided integral 3D images is magnified. An integral 3D image with an increased pixel count is generated by combining the magnified 3D images without gaps.

A convex lens is used for the MICOS, as shown in Figure 2. By using a convex lens, the image of the lens array plane is magnified on the rear side of the display plane, and a virtual image is formed. According to the lens formula, the following expression holds:

\[
\frac{1}{a} - \frac{1}{b} = \frac{1}{f_+},
\]

where \(a\) is the distance between the lens array plane and convex lens, \(b\) is the distance between the convex lens and virtual image plane, and \(f_+\) is the focal length of the convex lens. The magnification ratio \(m\) is expressed as follows:

\[
m = \frac{b}{a}
\]

2.2 Differences between the previous and proposed optical designs

A different method for increasing the pixel count of the integral 3D image using multiple direct-view displays was previously proposed.\(^{20,21}\) Table 1 compares the previous and proposed optical designs. There are four major differences.

The first difference is in the combination procedure. For the previous optical design, after MICOSs are placed in front of multiple direct-view displays and the two-dimensional (2D) images are combined on a diffuser plate into a single large 2D image, an integral 3D image is reconstructed using a lens array. On the other hand, for the proposed optical design, after the divided integral 3D images are reconstructed, the multiple integral 3D images are combined by MICOSs, as described in Section 2.1.

The second difference is in the MICOS design. The previous MICOS design is a complicated configuration comprising two biconvex lens arrays and a concave lens. Therefore, sufficient resolution cannot be obtained, owing to slight arrangement errors and errors in the lens processing accuracy. By contrast, the proposed MICOS design is a simple configuration using only a convex lens, one that suppresses any deterioration in resolution due to arrangement and lens processing errors.

The third difference pertains to the requirement for a diffuser plate. In the previous design, a diffuser plate with a large diffusion angle is required to reduce luminance unevenness, degrading the resolution owing to the diffusion of light. The proposed design does not

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**TABLE 1** Comparison between the previous and proposed optical designs

| Differences                  | Previous optical design                                      | Proposed optical design                                      |
|------------------------------|--------------------------------------------------------------|--------------------------------------------------------------|
| 1. Combination procedure     | After the 2D images are combined, the 3D image is reconstructed | After the divided 3D images are reconstructed, they are combined |
| 2. MICOS                     | Multiple lens arrays and a concave lens (complicated)        | A convex lens (simple)                                        |
| 3. Diffuser plate             | Necessary                                                   | Unnecessary                                                  |
| 4. Backlight of LCD panel     | Parallel light is necessary                                 | Diffused light can be used (OLED panel can also be used)     |

Abbreviations: 2D, two-dimensional; 3D, three-dimensional; LCD, liquid crystal display; MICOS, multi-image combining optical system; OLED, organic light-emitting diode.
need a diffuser plate, so there is no reduction in resolution.

The fourth difference regards the backlight of the LCD panel. In the previous design, multiple images are generated by the MICOS unless parallel light is used as the backlight of the LCD. To produce parallel light, a point light source must be combined with a convex lens, which increases the depth of the entire apparatus. By contrast, the proposed design can use diffused light, which enables making the apparatus thinner. Moreover, the proposed design can use not only LCDs but also OLEDs, further reducing the depth of the device.

3 | MULTIPLE-IMAGE COMBINATION WITH THE PROPOSED OPTICAL DESIGN

3.1 | Basic configuration for combining multiple images with the proposed optical design

Figure 3 shows the basic configuration of the proposed optical design for combining multiple images. As shown in Figure 3A, the image of the lens array plane is magnified to a virtual image with the MICOS (convex lens). Parts of adjacent magnified images overlap, and an overlap angle forms from these overlapping portions and the connecting point of adjacent convex lenses. When a 3D image is viewed from a position within the overlap angle (viewpoint A), multiple 3D images are seamlessly combined, as shown in Figure 3B, and can be viewed continuously. However, when it is viewed from a position that is outside the overlap angle (viewpoint B), a gap is generated between the multiple images, as shown in Figure 3C. That is, when the overlap angle is smaller than the viewing zone of the integral 3D image, the 3D image cannot be viewed continuously within the entire viewing zone.

3.2 | Viewing zone optimization using eccentric lens

In order to solve the problem presented in Section 3.1, a method using the eccentricity of the convex lens is proposed to increase the overlap angle. Figure 4 schematically shows the relationship between the lens array plane, convex lens plane, and virtual image plane for adjacent optical systems. Figure 4A shows the case without lens eccentricity; the central points of the convex lens and lens array plane are on the same vertical axis. Assuming that the distance between the lens array plane and convex lens plane is \( a \), the distance between the virtual image plane and convex lens plane is \( b \), the width of the image display plane is \( w_1 \), and the width of the display panel including the bezel is \( w_2 \); the length \( l \) of the overlapping portion and overlap angle \( \theta \) can be expressed as follows:

\[
l = \frac{b}{a}w_1 - w_2, \tag{3}
\]

\[
\theta = 2 \arctan \left( \frac{bw_1 - aw_2}{2ab} \right). \tag{4}
\]

If the distance between the lens array plane and the convex lens plane is increased, the overlap angle can be increased. However, this also increases the depth of the whole device. In order to enlarge the overlapping portion without the need for a larger device, the center of the lens
is decentered toward the outside, as shown in Figure 4B. Because the virtual image is accordingly shifted toward the inside, the overlap angle can be enlarged. Assuming that the eccentricity of the lens is $d$ and the focal length of the convex lens is $f_c$, the length $l'$ of the overlapping portion with the eccentricity of the lens and the overlap angle $\theta'$ can be expressed as follows:

$$l' = \frac{b}{a} w_1 - w_2 + 2 \left( \frac{b-a}{a} d \right), \quad (5)$$

$$\theta' = 2 \arctan \left\{ \left( \frac{bw_1 - aw_2}{2ab} \right) + \frac{d}{f_c} \right\}. \quad (6)$$

This equation shows that the overlap angle decreases with increasing bezel width, but this angle can be enlarged by increasing the eccentricity of the lens.

4 | EXPERIMENTS AND RESULTS

4.1 | Evaluation of the image quality using the previous and proposed optical designs

An experiment was conducted to evaluate the quality of the integral 3D images reconstructed by the previous and proposed optical designs. As shown in Figure 5A, a
reconstructed 3D image of a sinusoidal wave was recorded using a digital still camera (Nikon D750) with a high-resolution image pickup device, and the modulation transfer function (MTF) was calculated from the amplitude of the sinusoidal wave of the photographed image. Figure 5B–D shows examples of an original sinusoidal wave image, elemental images, and a reconstructed integral 3D image, respectively. The $F$ value and focal length of the camera lens were set to 16 and 50 mm, respectively. This means that the pupil diameter of the camera iris was about 3 mm, which is close to the pupil diameter of the average human.\textsuperscript{13} The viewing distance was assumed to be 700 mm, and the photographs were taken from this distance.

Table 2 presents the specifications of the experimental apparatus. Experiments were conducted to compare the first prototype of the previous design and the prototype of the proposed design. The display panels and lens arrays had the same specifications. The MTF was measured as follows:

1. An integral 3D image of a sinusoidal wave was displayed by using the display panel, lens array, and MICOS.
2. An integral 3D image of a sinusoidal wave was photographed with the digital still camera.
3. The luminance data for one line at the center of the photographed image were extracted and fitted to a sinusoidal wave using the least-squares method, and the MTF was calculated from the amplitude.
4. The above procedure was performed for sinusoidal waves of various spatial frequencies.

For the lens array, the theoretical spatial frequency characteristics can be plotted as shown in Figure 6 on the basis of the principle of the integral 3D system.\textsuperscript{10} The MTF of the reconstructed 3D image was measured at a position of 100 mm in front of the lens array plane. The upper limit for the spatial frequency of the 3D image at this position was 130.8 cycles per radian (cpr).

### Table 2: Specifications for the image quality evaluation experiment

| Specification                  | Nikon D750                   | 1920 × 1080 pixels | 55.5 μm | square/square | 1.21 mm/2.42 mm | 0.5 mm | 0.52 mm | −145 mm | 60° |
|--------------------------------|-------------------------------|-------------------|--------|---------------|-----------------|--------|--------|---------|-----|
| Digital still camera           | Camera                        | Number of pixels  | 6016 × 4016 pixels | 50 mm | 16 |
| LCD panel                      | Number of pixels              | 1920 × 1080 pixels | 55.5 μm | square/square | 1.21 mm/2.42 mm | 0.5 mm | 0.52 mm | −145 mm | 60° |
| Lens array                     | Arrangement/shape             | square/square     | 1.21 mm/2.42 mm | 0.5 mm | 0.52 mm | −145 mm | 60° |
| MICOS of the previous design   | Lens pitch of the lens array  | 0.5 mm            | 0.52 mm | −145 mm | 60° |
| MICOS of the proposed design   | Focal length of the convex lens | 175 mm           | 175 mm |

Abbreviations: FWHM, full width at half maximum; LCD, liquid crystal display; MICOS, multi-image combining optical system.
Measurements were carried out by incrementing the spatial frequency in 10 steps up to the upper limit. Figure 7 shows the MTF results. The results of the previous and proposed optical designs are plotted as red and blue lines, respectively. The MTF value of the proposed design was sufficiently higher than that of the previous design at all spatial frequencies.

Figure 8A and 8B shows examples of integral 3D images reconstructed by the previous and proposed optical designs, respectively, by arranging the display panels horizontally and vertically in a 2 × 2 array and combining four display images. The integral 3D image reconstructed by the previous design has low image quality and low contrast. On the other hand, the integral 3D image reconstructed by the proposed design has high contrast and improved image quality. Figure 8C and 8D shows photos of a device with the previous and proposed optical designs, respectively. Because the previous design requires a parallel light for the backlight, the depth of the whole device is considerable, at about 600 mm. On the other hand, because the proposed design can use diffused light as the backlight, the device is much thinner, at about 110 mm.
4.2 Verification of the viewing zone optimization method

Verification experiments were conducted to confirm the effectiveness of the viewing zone enhancement method described in Section 3.2. Figure 9 shows the apparatus configuration. For a single LCD panel, a black image was input as a virtual bezel, and the display area was divided into two. Two integral 3D images were displayed in the horizontal direction at a distance of 10 mm with a lens array and combined without gaps using the proposed MICOSs. Table 3 presents the specifications of the experiment apparatus. Two types of the proposed MICOS were prepared: with and without the lens eccentricity. The experiment was performed to verify whether the viewing zone is enlarged by the use of an eccentric lens. Figure 10 shows the verification results for viewing directions of ±8.8° and 0° (A) without and (B) with the lens eccentricity. Without this eccentricity, a gap occurred between the two images at the viewing direction of ±8.8°, which resulted in discontinuous images. On the

**TABLE 3** Specifications of the apparatus in the principle verification experiment with the viewing zone optimization method

| Specification                                      | Value                  |
|----------------------------------------------------|------------------------|
| Number of pixels per single display                | 430 (H) × 430 (V)      |
| Pixel density of display panel                     | 185 ppi                |
| Pitch of lens array/focal length of lens array     | 1.2 mm/2.4 mm          |
| Focal length of convex lens for MICOS \( f_c \)     | 175 mm                 |
| Eccentricity of lens, \( d \) (without/with)      | 0 mm/28.5 mm           |
| Distance between two images \( c \) (virtual bezel width) | 10 mm                 |

**FIGURE 10** Integral three-dimensional (3D) image viewed from the viewing directions of ±8.8° and 0°: A, Without; B, With the eccentricity of the lens. The motion parallax can be confirmed from the positional relationship between the front doll and the background cloud.

**TABLE 4** Specifications of the multi-image combining apparatus using a high-density OLED panel

| Specification                                      | Value                  |
|----------------------------------------------------|------------------------|
| Number of pixels per single display                | 3673 (H) × 2066 (V)    |
| Number of display areas                            | 4                      |
| Pixel density of display panel                     | 1058 ppi               |
| Pitch of lens array/focal length of lens array     | 0.5 mm/1.06 mm         |
| Focal length of convex lens for MICOS \( f_c \)     | 175 mm                 |
| Number of elemental images after multiple images are combined | 311 (H) × 175 (V) |
| Viewing angle                                      | 20.6° (both horizontally and vertically) |
| Size of 3D image before and after multiple images are combined | Before: diagonal 4.0 in After: diagonal 9.1 in |

Abbreviations: 3D, three-dimensional; MICOS, multi-image combining optical system; OLED, organic light-emitting diode.
other hand, no gap occurred with the eccentricity of the lens. The effective viewing angle was 8.3° without the lens eccentricity but 21.8° with the eccentric lens. Thus, the eccentric lens increased the effective viewing angle by about 2.6 times.

There is a correlation between the eccentricity of the lens and the image quality of 3D images. As the eccentricity increases, the light rays are incident on the part away from the center of the lens, which is considerably affected by aberration, and it is considered that the image quality deteriorates, and image distortion occurs. Therefore, a convex Fresnel lens was used as a lens of MICOS. A Fresnel lens enables manufacturing a lens with a large aperture, and it suppresses image quality

![Image of 3D images from different viewpoints](image_url)

**FIGURE 12** Changes in the appearance of the reconstructed integral three-dimensional (3D) image from different viewpoints (Movie S1): A, Entire images; B, Partially enlarged images. The motion parallax can be confirmed from the positional relationship between the character “3D” and the hand of the doll
deterioration and image distortion due to the lens, even if the lens has a large eccentricity. A lens with a focal length of 175 mm and an eccentricity of 28.5 mm was used in this experiment, and image quality deterioration and distortion due to the lens were not observed.

4.3 Combining multiple images when using a high-density display panel

The viewing zone was enhanced by the eccentric lens, and a multi-image combining experiment was conducted with a high-density display panel. Figure 11 shows the configuration of the prototype apparatus, and Table 4 presents its specifications. A high-density OLED panel22 with 8K resolution and 1058 ppi pixel density was used as the display device. Part of the display area was set in black, it was virtually divided into four areas, and the four images were then combined. The bezel width can be made variable by using the virtual bezel, allowing multi-image combination experiments to be performed flexibly. The elemental images for input to the four display areas were created by considering the overlapping portion of the magnified image. Multiple convex lenses for combining multiple images were integrally molded on a single acrylic plate to form a Fresnel lens array and thus reduce the unnaturalness of the image connecting portion. Figure 12 shows the changes in appearance of the reconstructed integral 3D image from different viewpoints. As shown in the partially enlarged images in Figure 12B, it can be seen that there is motion parallax in the positional relationship between the character “3D” and the hand of the doll, according to the viewpoints. With the use of a high-density OLED panel with 8K resolution, the number of elemental images increased by approximately 3.2 times than that of the fabricated device described in Section 4.1, and the depth of the device was reduced by more than half, from 110 to 47 mm. Combining even more integral 3D images would likely be possible with the appropriate optical system.

5 CONCLUSION

A method for high-quality multi-image combination using an integral 3D display system with a direct-view display was proposed. Unlike the previous optical design, which required a diffuser plate and a complex MICOS, the proposed optical design is simple and does not require a diffuser plate. Furthermore, although the previous design required a parallel light for the LCD backlight, the proposed design can use diffused light, which reduces the depth of the whole device.

The image quality of the previous and proposed optical designs was experimentally compared, and the results demonstrated that the MTF was significantly improved. A method was also proposed for expanding the effective viewing angle of the integral 3D display by using an eccentric lens with the proposed optical design. A principle verification experiment was carried out, and the results showed that the effective viewing angle increased by about 2.6 times. The proposed MICOS and the method for enhancing the effective viewing angle were applied to an apparatus with a high-density OLED panel to realize very high-quality multi-image combination. The number of elemental images was 311 (H) × 175 (V), the viewing angle was 20.6° in both the horizontal and vertical directions, and the display size had a diagonal of 9.1 in. Furthermore, the OLED panel enabled reducing the depth of the whole device to 47 mm. This method for multi-image combination allows the display size to be enlarged and the apparatus to be more compact, both of which may facilitate the home application of 3D displays in the future.

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**SUPPORTING INFORMATION**

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