High definition integral floating display with multiple spatial light modulators

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ABSTRACT

In this paper, a high-definition integral floating display is implemented. Integral floating display is composed of an integral imaging system and a floating lens. The integral imaging system consists of a two-dimensional (2D) display and a lens array. In this paper, we substituted multiple spatial light modulators (SLMs) for a 2D display to acquire higher definition. Unlike conventional integral floating display, there is space between displaying regions of SLMs. Therefore, SLMs should be carefully aligned to provide continuous viewing region and seamless image. The implementation of the system is explained and three-dimensional (3D) image displayed by the system is represented.

Keywords: Three-dimensional display, integral floating display, spatial light modulator, viewing window

1. INTRODUCTION

The history of three-dimensional (3D) display is more than 100 years [1]. Although hologram is thought as an ultimate solution, researchers and companies use multiview methods or stereoscopy with glasses to achieve practical solutions although they are less perfect. Typical methods used in commercialized multiview 3D display are parallax barrier and lenticular sheet methods, which have parallax in horizontal direction only. However, many researchers are studying for full parallax 3D displays or super-multiview 3D displays, which are more ideal than currently commercialized methods and more practical than hologram.

Integral imaging, whose concept is illustrated in Fig. 1, is a famous full parallax 3D display which was firstly proposed by G. Lippmann in 1908 [2]. Actually, lenticular method is a reduced version of integral imaging in horizontal direction.

Figure 1. Concept of integral imaging.
Integral imaging acquires full parallax at a price of lower resolution than other 3D displays with horizontal parallax only. Also, it provides almost-continuous viewpoints to observers. Researchers have tried to resolve demerits of integral imaging such as pseudoscopic problem, narrow depth expression range and limited viewing angle [3-6].

Super-multiview is a 3D display system which provides multiple viewpoints, of which spacing between viewpoints is smaller than the size of pupil [7-9]. In this way, the system provides more than one view to one eye of observer. This method is expected to resolve the conflict between physiological depth perception cues, such as accommodation and binocular disparity. However, the system sacrifices its resolution far more than the integral imaging to achieve super-multiview attribute. Also, super-multiview systems normally give up vertical parallax because it requires too huge information to provide full parallax super-multiview. In this paper, we want to pursue a practical solution for full parallax 3D image display method.

An integral floating display is a combination of integral imaging and a large convex lens or concave mirror [10-12]. Throughout this paper, the large convex lens is called a floating lens. The integral imaging provides a 3D image to the floating lens. The floating lens forms a floating image in the vicinity of observer. Its concept is shown in Fig. 2. The integral floating system has full parallax and continuous viewpoints as in the case of integral imaging system. Moreover, it has larger depth expression range and greater feel of depth than an integral imaging by help of the floating lens. However, the integral floating display suffers from reduction in resolution to provide full parallax.

In this paper, we implement an integral floating display using multiple SLMs to achieve high resolution full parallax 3D display system. Each SLM provides one elemental image for one elemental lens. Unlike conventional integral imaging or integral floating display, there is spacing between neighbor SLMs. This spacing can be overcome by carefully aligning SLMs based on the principle of viewing window formation.

2. VIEWING WINDOW

Limited viewing angle is well known and well analyzed characteristic of integral imaging. The viewing angle is characterized by the distance between elemental image set and lens array and the aperture size of elemental lens. The same spatial relationship also exists in integral floating display. Additionally, there is a floating lens in integral floating display. By the role of the floating lens, limited viewing angle in integral imaging is changed to limited viewing space in integral floating display. Viewing window is this 2D space only through which 3D floating image is observable. Since the introduction of integral floating display, viewing window has been analyzed and developed [12, 13]. To determine
the position of SLMs, the principle of viewing window formation is briefly reviewed. Figure 3 illustrates the principle of viewing window formation.

In Fig. 3, there are marginal rays for each elemental lens whose leaving angle from the lens surface is maximum, which is the same as viewing angle. In this illustration, 2D situation is assumed so that there are two marginal rays in upper and lower directions. These marginal rays are parallel in conventional integral imaging. Therefore, parallel marginal rays converge at the focal plane of the floating lens. The space between these converging points is the viewing window. A research on viewing region of integral floating display reports that the position of viewing window can be modified by controlling the elemental image area. In such situation, the marginal rays proceed as if they diverge from certain distance [13].

The top point of the viewing window is the converging point of upper directional marginal rays and bottom point of the viewing window is the converging point of lower directional marginal rays. However, the upper directional marginal rays start from the bottom point of elemental image and the lower directional marginal rays start from the top point of elemental image. Thus, the viewing window can be thought as superposed upside-down images of elemental images. Therefore, SLMs should be aligned in such a way that every SLM is superposed on the same location as shown in Fig. 4.
In Fig. 4, marginal rays are less steep than the marginal rays in Fig. 3 because SLM in Fig. 4 is smaller than the elemental image area in Fig. 3. In Fig. 4, SLMs are aligned to make marginal rays be parallel to one another. Then the marginal rays converge after refraction on floating lens. The viewing window is again formed on the focal plane as in Fig. 3. As in the previous discussion, the viewing window can be moved to desired position by controlling the spacing among SLMs.

Here, we want to emphasize the spacing between SLMs does not cause discontinuities in viewpoints. The viewpoints would be discontinuous if there is spacing between elemental lenses, not between SLMs. Spacing between SLMs only makes viewing window smaller and has no effect on the viewpoints.

In our implemented system, SLMs are placed just behind its corresponding elemental lens. The distance between centers of neighbor SLMs is the same as the distance between centers of neighbor elemental lenses. The marginal rays from integral imaging system are parallel to one another as in Fig. 4. The viewing window is formed at the focal plane of the floating lens. The viewing window is smaller because SLM is smaller than the elemental image area of conventional setup. However, it is our choice to use SLM to acquire higher resolution. Smaller viewing window is a tradeoff to higher resolution in the implemented system.

3. STRUCTURE OF THE SYSTEM

The structure of the system is illustrated in Fig. 5. It is composed of four controllers, 12 SLMs, lens array, and a floating lens. The SLMs are acquired by disassembling full color liquid crystal display (LCD) projectors. They are black and white and three of them with color filters form a full color SLM unit. We implemented black and white 3D display in our system. One controller can handle three SLMs, and four controllers can handle 12 SLMs. 12 SLMs are aligned on a specially made steel supporter to locate SLMs exactly in desired position. There are six SLMs in horizontal direction and two SLMs in vertical direction. The distance between the centers of neighbor SLMs is designed to be the same as the distance between the centers of neighbor elemental lenses, as discussed in the previous section. Lens array composed of 12 elemental lenses is placed in front of the SLM array. Each elemental lens is in front of its corresponding SLM. The SLM array and lens array combine to constitute an integral imaging system. A floating lens is placed in front of the integral imaging system. The floating lens forms a viewing window at the focal plane and produces a 3D floating image in the image space.

The specifications of devices and distances among them are shown in Table 1.
Table 1. Specifications and distances among devices

<table>
<thead>
<tr>
<th>Element</th>
<th>Specifications</th>
<th>Characteristics</th>
</tr>
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<tbody>
<tr>
<td>SLM array</td>
<td>Pixel pitch</td>
<td>12.5 μm × 12.5 μm</td>
</tr>
<tr>
<td></td>
<td>Resolution</td>
<td>1024 × 768</td>
</tr>
<tr>
<td></td>
<td>Display area</td>
<td>12.8 mm × 9.6 mm</td>
</tr>
<tr>
<td></td>
<td>Number of SLMs</td>
<td>6(H) × 2(V)</td>
</tr>
<tr>
<td>Lens array</td>
<td>Focal length</td>
<td>50.8 mm</td>
</tr>
<tr>
<td></td>
<td>Pitch of elemental lens</td>
<td>25.4 mm</td>
</tr>
<tr>
<td></td>
<td>Number of elemental lenses</td>
<td>6(H) × 2(V)</td>
</tr>
<tr>
<td>Floating lens</td>
<td>Focal length</td>
<td>175 mm</td>
</tr>
<tr>
<td></td>
<td>Aperture</td>
<td>300 mm</td>
</tr>
<tr>
<td>Distances</td>
<td>From SLM array to lens array</td>
<td>50.8 mm</td>
</tr>
<tr>
<td></td>
<td>From lens array to floating lens</td>
<td>243 mm</td>
</tr>
</tbody>
</table>

As shown in Table 1, the display area is about two times smaller in horizontal direction and two and half times smaller in vertical direction than the elemental lens. This is amount of the area loss of viewing window. Figure 6 shows the SLM array attached on the specially produced steel supporter. As shown in Fig. 6, the spacing between displaying areas of SLMs are restricted by the width of frame of SLM. In fact, it seems that the space for screws fixing the position of SLM occupies large space in the frame. If we can specially manufacture an SLM whose frame is thinner, then the space between neighbor SLMs would be reduced. Manufacture of SLM array itself can also be a good solution. However, it is an economical solution for 3D display that we were looking for. If integral floating display is commercialized and SLMs for integral floating is manufactured, then they will provide larger viewing windows than that for LCD projectors.

Figure 6. SLM array fixed on a steel supporter.
The actual experimental setup is presented in Fig. 7. To minimize aberration, Fresnel lenses are used for lens array and floating lens. A fluorescent tube is used as a backlight for SLM array, and cheap oilpaper is attached on the back of the SLMs to diffuse the light from fluorescent tube. Also, polarizers are attached on the back and front of the SLMs.

![Experimental Setup](image)

**Figure 7.** Actual experimental setup of the proposed system.

### 4. EXPERIMENTAL RESULTS

To verify the feasibility of proposed system, an elemental image set for a 3D image containing two 3D objects is produced. A cube with texture on its sides and a teapot is used for 3D objects. Spatial relationship among 3D objects and integral floating display is illustrated in Fig. 8.

![Experimental Setup](image)

**Figure 8.** Experimental setup.
The viewing window is located at the focal length of the floating lens. The 3D image of a teapot is behind the viewing window by 30mm, while the 3D image of a cube is in front of the viewing window by 30mm. The depth difference between two 3D images is 60mm. The observer sees seamless floating 3D image when he or she is 611mm away from the floating lens. The floated mapping is used for elemental image generation [14].

Figure 9 shows the experimental results. The floating 3D image is observed from five different viewing positions. The texture on the cube is clearly observed. The relative displacement between teapot and cube changes as viewing position changes. Also, the shapes of the 3D objects also change according to the viewing positions.

![Image of floating 3D image](http://example.com/image.jpg)

Figure 9. Experimental results showing disparities of 3D floating image.

5. CONCLUSION

An integral floating display can provide full parallax 3D image with large feel of depth, but it suffers low resolution. To implement a high-definition integral floating display, we used multiple SLMs. Each SLM is placed behind its corresponding elemental lens. However, the spacing between neighbor SLMs reduce the size of viewing window. Smaller viewing window is a tradeoff to higher resolution. The experimental results show high-definition 3D image with appropriate disparities according to the viewing position of observer.

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