Three-dimensional display based on integral imaging

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Abstract
Integral imaging is an attractive three-dimensional display technique providing full-parallax full-color three-dimensional images in real-time without any viewing aids. In this paper, we present the recent progress on the three-dimensional display based on integral imaging focusing on its depth and viewing angle enhancement and the three-dimension/two-dimension convertibility.

1. Introduction
There have been numerous approaches to realize a display delivering vivid three-dimensional (3D) images to the observers. Some techniques – called autostereoscopic binocular display – provide depth perception by separately projecting left and right views to the corresponding eyes. A lenticular lens and a parallax barrier are well-known devices for this purpose. Limited viewing positions and eye discomfort, however, are prime drawbacks. Other techniques – called volumetric or holographic display – display 3D images by reproducing their voxels using volume sweeping or by reproducing the wavefront using holography. These methods, however, requires high performance devices that can hardly be realized in near future.

Integral imaging, placed between the autostereoscopic display and the volumetric/holographic display, is the 3D display technique of high prospect. It provides full-parallax full-color 3D images in real-time with compact system configuration.[1] Full-parallax including vertical and horizontal directions and continuous viewing positions are the features distinctive from the autostereoscopic displays. Compact system configured using manageable devices is the advantage over the volumetric/holographic displays. With these superior features, integral imaging attracts growing attention recently.

Figure 1 shows the principle of the integral imaging. Integral imaging consists of two processes – pickup and display. In the pickup process, a 3D object is imaged through the lens array. Each elemental lens constituting the lens array forms a perspective of the object, called elemental image, and all elemental images formed by the lens array are captured by a camera. In the display process, the elemental images are displayed on the flat panel display device like liquid crystal display (LCD). Then the elemental images are integrated by the lens array into the 3D images at the original location of the object.

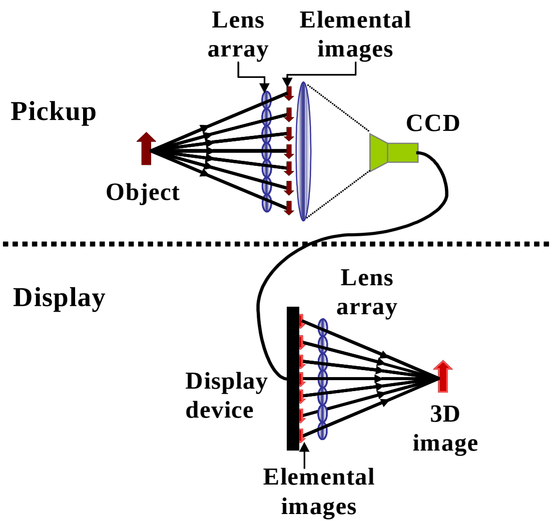


Figure 1. Principle of integral imaging

Major issues on the integral imaging are its viewing angle, available depth range, and 3D / two-dimension(2D) convertibility. Though integral imaging provides realistic 3D images, the viewing angle where the 3D images are visible and the depth range where the 3D image can be located are not sufficient at this time. The fact that only the 3D images can be displayed and the 2D images cannot be displayed is another factor limiting the practical value of the integral imaging. In this paper, we present our recent progress on these issues. Curved lens array scheme for the viewing angle enhancement and layered panel scheme for depth enhancement are described. 3D/2D convertible scheme using polymer dispersed liquid crystal (PDLC) is also presented.

2. Viewing angle

2.1 Viewing angle limitation

Figure 2 shows the basic reason of the viewing angle limitation. The limitation arises originally because the display panel area allocated to each elemental lens is limited.[2],[3] In integral imaging, each elemental lens has its own area on display panel and each elemental image cannot be displayed out of that area as in the figure. If the elemental image exceeding the corresponding area is displayed, the generated 3D image will be distorted due to overlapping of the neighboring elemental images or will be flipped due to imaging through non-corresponding elemental lens. This limitation of the displayed range of the elemental image restricts the viewing angle ψ as $\psi=2\tan^{-1}(\varphi/2g)$ where φ is the elemental lens pitch and g is the gap between the lens array and the display panel.

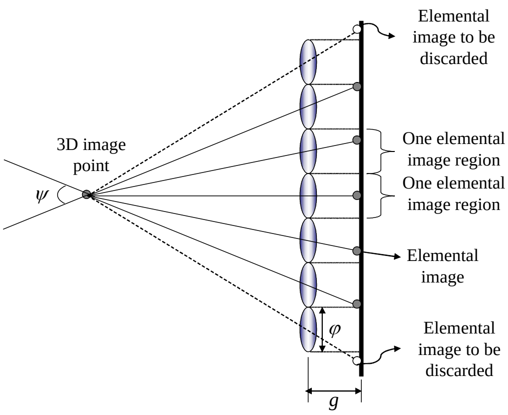


Figure 2. Viewing angle limitation

2.2 Viewing angle enhancement using curved lens array and screen

In order to increase the viewing angle, we tried curved lens array scheme shown in Fig. 3(a).[4] The lens array is curved laterally with a uniform radius of curvature. The elemental image region is also redefined according to the curvature radius. The area on the display panel between the lines extending from the curvature center of the lens array to the edges of the corresponding elemental lens is assigned to the elemental image region of the corresponding elemental lens. In this configuration, for a 3D image located in the vicinity of the curvature center of the lens array, its all elemental images are placed within the corresponding elemental image regions, making it possible to display all elemental images without discarding. Consequently, the viewing angle is enhanced laterally. Figure 3(b) shows the experimental result. It can be seen that the viewing angle 16° of the conventional integral imaging is enhanced to 30° by the curved lens array scheme.

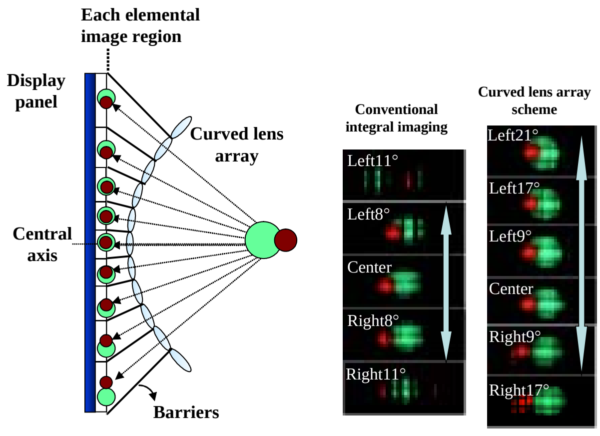
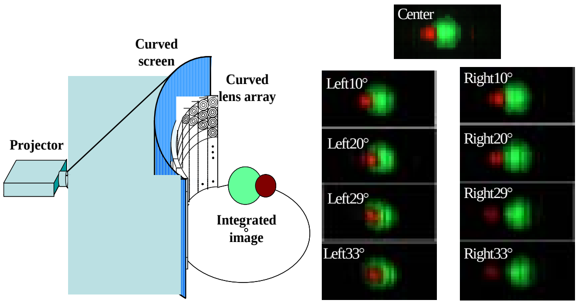


Figure 3. Curved lens array scheme (a) configuration (b) experimental result

Though the curved lens array scheme eliminates the viewing angle limitation caused by the restricted elemental image region, it still has viewing angle limitation, which arises from the gap mismatch. In the curved lens array scheme, the gap between the lens array and the display panel is not uniform but increases as the elemental lens deviates farther from the central axis. This gap mismatch causes large off-focusing and limits the viewing angle.



(a) **(b)**

Figure 4. Curved lens array and screen scheme (a) configuration (b) experimental result

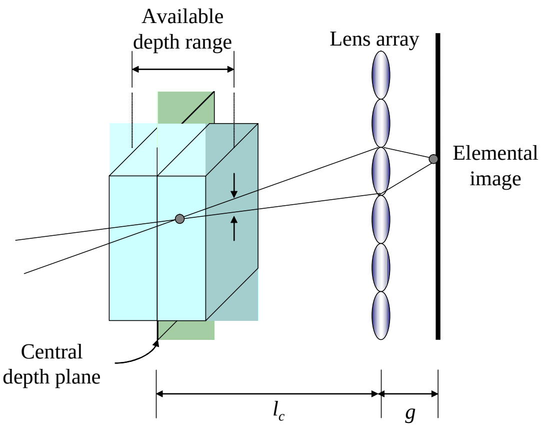


Figure 5. Depth range limitation

To remove the gap mismatch, we enhanced the system by curving the display panel as well as the lens array.[5] Since there is no commercially available flexible display at this time, we curved the screen and projected the elemental images on it. Figure 4(a) shows the configuration of the curved lens array and screen system and Fig. 4(b) shows the experimental result. We can see that the viewing angle is remarkably increased to 66°.

3. Depth range

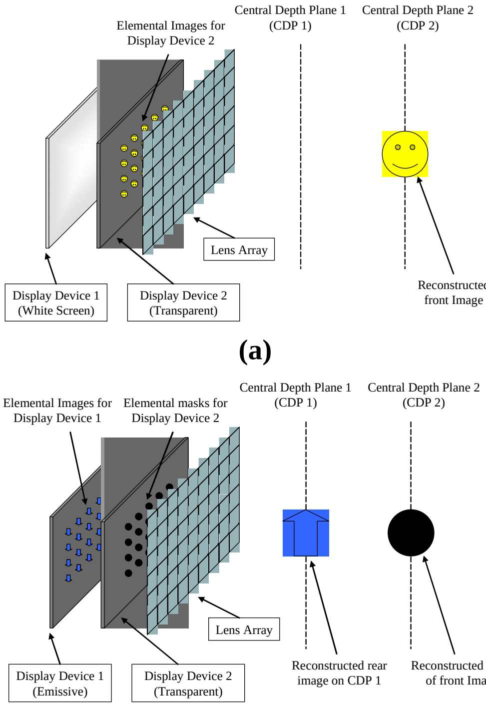
3.1 Depth limitation

The depth range wherein the 3D image can be located is also limited in integral imaging. Figure 5 shows this point. In integral imaging, the elemental images on the display panel are imaged by the corresponding elemental lenses, being integrated at the desired 3D location. Since the 3D image generation is based on the imaging by the elemental lens, there exists a focal plane whose location is determined by the Gauss lens law. (Hereafter let us call this focal plane a central depth plane according to the convention of the literatures concerning integral imaging.) Therefore the resolution of the integrated 3D image is best at the central depth plane and it degrades as the 3D image goes far from the central depth plane. This fact limits the available depth range under a finite area around the central depth plane.[6]

3.2 Depth enhancement using layered panel scheme

The basic principle of the layered panel scheme is shown in Fig. 6.[7] As shown in Fig. 6(a), a transparent display device (display device 2) is located between the display device 1 and the lens array. Since the display device 2 is transparent, it is possible to locate elemental images on both display devices. Two central depth planes – CDP 1 and CDP 2 – are formed by the display device 1 and display device 2, respectively, through the lens array. Since the number of the central depth planes is increased from one (in the conventional integral imaging) to two (in the layered panel scheme), the depth range wherein the 3D image is located is doubled, which provides more vivid depth perception.

In operation, two phases corresponding to each central depth plane are time-multiplexed as shown in Fig. 6. In the front image phase, elemental images for the front 3D images are displayed on display device 2 and display device 1 becomes completely white to illuminate the display device 2. In the rear image phase, the elemental images for the rear 3D image are displayed on display device 1 and the elemental images for front 3D image are displayed on the display device 2 in black color. The blacked elemental images for the front 3D images provide realistic occlusion effect between the front and rear 3D images.

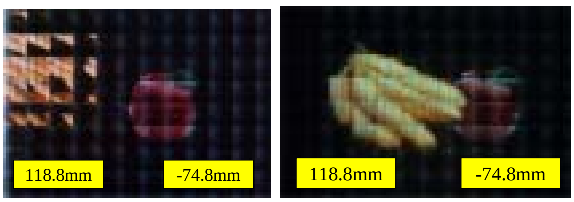


(a)

(b)

Figure 6. Layered panel scheme (a) front image phase (b) rear image phase

Figure 7 shows the experimental result. We can see that two 3D images with different depth are displayed clearly in the layered panel scheme while they are significantly distorted in the conventional integral imaging.



(a) **(b)**

Figure 7. Experimental result (a) conventional integral imaging (b) layered panel scheme

4. 3D/2D convertibility

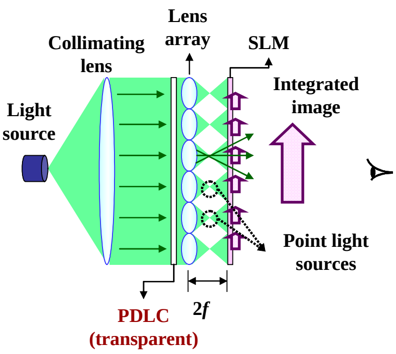
4.1 3D only property

Another great issue of integral imaging is 3D/2D convertibility. In integral imaging configuration, the lens array is located in front of the display panel; i.e. closer to the observer. Therefore all images are seen through the lens array, and resultantly, 2D image cannot be displayed. In order to be more valuable in practical point of view, integral imaging should be capable of displaying both of 3D and 2D images, because a 3D only display that cannot display 2D images is expected to find only limited few applications.

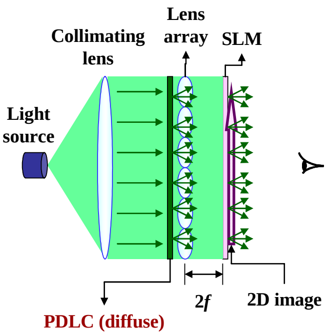
4.2 3D/2D convertible integral imaging

The concept of the proposed 3D/2D convertible integral imaging scheme is shown in Fig. 8.[8],[9] On contrary to the conventional integral imaging that locates the lens array in front of the display panel closer to the observer, the proposed 3D/2D convertible integral imaging scheme places the lens array behind the transmission-type spatial light modulator (SLM) at a distance of twice of the focal length of the lens array. A PDLC is also attached at the back plane of the lens array.

The 3D/2D convertible integral imaging operates in two modes – 3D and 2D modes. In the 3D mode, the PDLC is electrically controlled to be transparent. Then the collimated illumination light is focused by the lens array to form the point light source array at the focal plane of the lens array. The SLM modulates the intensity of the light rays from the point light sources properly and finally 3D image is displayed in the increased depth range.



(a)



(b)

Figure 8. Concept of the 3D/2D convertible integral imaging (a) 3D mode (b) 2D mode

The principle of the 3D image formation in the 3D/2D convertible integral imaging is more clearly depicted in Fig. 9. In order to reproduce a voxel **P** in Fig. 9, its elemental images are displayed where the lines extending from **P** to the point light sources are intersecting the SLM. Then the light rays from the point light sources are integrated as a voxel at **P**. By reproducing every voxels of the desired 3D images, 3D images can be displayed. In 2D mode, the PDLC is controlled as diffusive as shown in Fig. 8(b). The collimated back illumination is scattered by the PDLC, and this scattered field is relayed by the lens array to the SLM. In this case, each pixel in the SLM is illuminated from effectively all directions. Therefore the observer sees 2D images on the SLM plane with its full resolution.

The experimental result is shown in Fig. 10. Figure 10(a) shows the displayed 3D images. The different perspectives according to the observation directions state the 3D property of the displayed image. Figure 10(b) is the displayed 2D image. We can see that the 2D image is displayed clearly with full resolution.

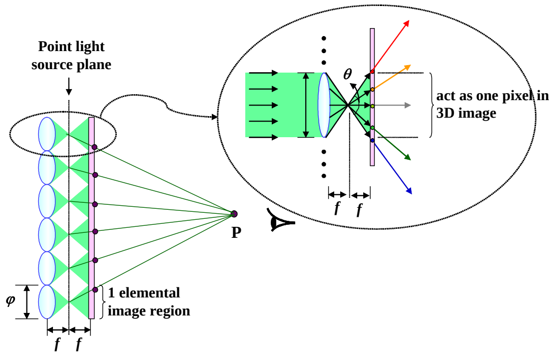
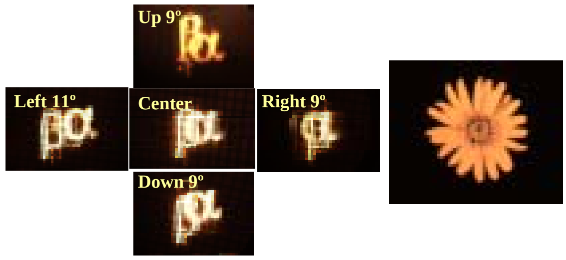


Figure 9. 3D image formation in 3D/2D convertible integral imaging



(a) (b)

Figure 10. Experimental result (a) 3D mode (b) 2D mode

Acknowledgment

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