Curved Projection Integral Imaging Using an Additional Large-Aperture Convex Lens for Viewing Angle Improvement

Joobong Hyun, Dong-Choon Hwang, Dong-Hak Shin, Byung-Gook Lee, and Eun-Soo Kim

In this paper, we propose a curved projection integral imaging system to improve the horizontal and vertical viewing angles. The proposed system can be easily implemented by additional use of a large-aperture convex lens in conventional projection integral imaging. To obtain the simultaneous display of 3D images through real and virtual image fields, we propose a computer-generated pickup method based on ray optics and elemental images, which are synthesized for the proposed system. To show the feasibility of the proposed system, preliminary experiments are carried out. Experimental results indicate that our system improves the viewing angle and displays 3D images simultaneously in real and virtual image fields.

Keywords: Three-dimensional (3D) imaging, integral imaging, lenslet array, viewing angle.

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I. Introduction

Since integral imaging was first proposed by Lippmann in 1908, it has been a promising three-dimensional (3D) imaging and display technique with full parallax and incoherent light [1]-[7]. In general, integral imaging consists of both pickup and display parts. The pickup part of integral imaging is carried out by a lenslet array and a two-dimensional (2D) image sensor. In the pickup part, rays coming from a 3D object are optically recorded as elemental images, which have their own perspective of a 3D object, by the lenslet array and 2D image sensor. The display part is the reverse of the pickup part. The recoded elemental images are displayed on a display panel, and then a 3D image is reconstructed through the lenslet array in front of the display panel.

Although integral imaging has many advantages, including the full parallax, a continuous viewing point, and full color images, it also has disadvantages, such as the narrow viewing angle and low resolution. Recently, to improve the viewing angle, curved integral imaging systems using a curved lens array have been reported [8], [9]. However, their optical implementation has been limited to only horizontal systems because it is difficult to fabricate a curved lens array and a curved display panel. To overcome this problem, a curved integral imaging system was proposed which additionally uses a large-aperture convex lens [10]. This system provides a simple structure due to the use of the well-fabricated flat devices and the additional large-aperture convex lens.

Recently, several projection integral imaging (PII) systems with 2D image projectors have been reported [9], [11]-[13]. It is easy to implement the simple structure of the integral imaging display system using PII because of simple mapping between the elemental images and the lenslet array. In 2004, Jang and Javidi proposed the PII system, in which high resolution elemental images were displayed by using multiple projectors; thus, the resolution of reconstructed 3D images was improved [11]. They also proposed a PII system in which the lenslet array is in contact with the large-aperture concave lens in order to pickup and display the large 3D objects that are far away [12]. In 2004, Kim and others proposed a curved PII (CPII) system which uses a curved lenslet array to improve the viewing angle [9]. However, this system has been limited to only horizontal systems, and it requires complex modification of the proper elemental images.

In this paper, to improve the horizontal and vertical viewing angles, we propose a CPII system which uses a large-aperture convex lens in the conventional PII system. The proposed system has a simple structure due to the use of a well-fabricated flat lenslet array and a large-aperture convex lens. To obtain the simultaneous display of 3D images through real and virtual image fields, we introduce a computer-generated pickup method, and elemental images are synthesized for the proposed system. To show the usefulness of the proposed system, preliminary experiments are carried out and some experimental results are presented.

II. Proposed CPII System

1. System Structure

The ideal configuration of the CPII system using a curved lenslet array, a curved screen, and a 2D image projector is shown in Fig. 1(a). Using a curved lenslet array and a curved screen provides a wide viewing angle; however, it is difficult to fabricate curved devices. In addition, the projected elemental images must be modified for projection on the curved screen. To overcome this problem, we propose a CPII system which has the equivalent effect of a curved lenslet array: it uses a flat lenslet array and a large-aperture convex lens as shown in Fig. 1(b). With a flat lenslet array, a flat screen can be used. The additional large-aperture convex lens provides a multidirectional curvature effect and a wide viewing angle.

2. Synthesis of Elemental Images for Real and Virtual Display of 3D Images

To obtain elemental images for the proposed CPII system, we can use a computer graphics (CG) pickup method. In this paper, the CG pickup technique based on an ABCD matrix [10] is extended to the synthesis of elemental images for real and virtual display of 3D images. To simplify the illustration of ray analysis, we consider 1D analysis. The extension to 2D analysis is straightforward.

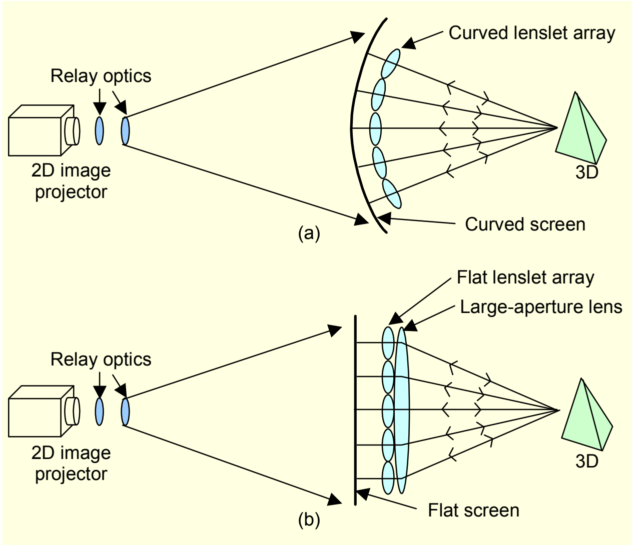

Fig. 1. Ideal CPII system and the (b) proposed CPII system.

First, consider the elemental images of a 3D object located in the real image field. Figure 2 shows the scheme to synthesize the elemental images in real image field of the proposed CPII system. To simplify the explanation, we suppose the use of a pinhole array and a conventional large-aperture thin lens. Let us define the distance between the lenslet array and the display panel as g and the focal length of the thin lens as f. As shown in Fig. 2, we consider a ray from the n-th pixel of the k-th elemental image. This starting ray goes toward the k-th lenslet and is given by

$$\begin{bmatrix} H_n^k(z=0) \\ A_n^k(z=0) \end{bmatrix} = \begin{bmatrix} kp+nd \\ -nd/g \end{bmatrix}, \quad (1)$$

where $H(z)$ and $A(z)$ mean the height of the ray and the starting angle at position z, respectively; p is the pitch of the lenslet; and d is the size of a pixel in the elemental image. When z=g, the ray becomes

$$\begin{bmatrix} H_n^k(g) \\ A_n^k(g) \end{bmatrix} = \begin{bmatrix} kp \\ -nd/g \end{bmatrix}. \quad (2)$$

For the rays that intersect at the corresponding pinhole, the confined transmission matrix from the elemental image plane z=g to an arbitrary distance z_r is calculated by

$$T_r = \begin{bmatrix} 1 & z_r - g \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}. \quad (3)$$

From (2) and (3), we can calculate the height of each ray at the distance z_r. Then, we obtain

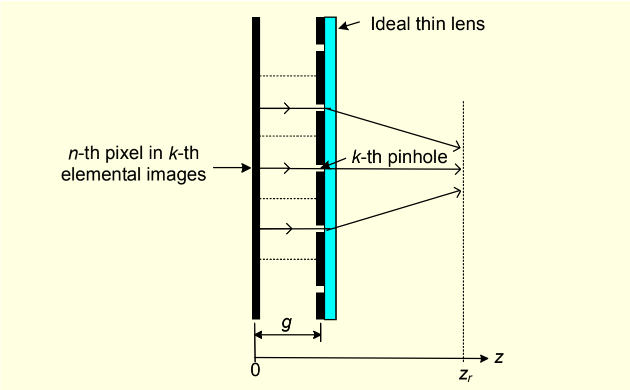

Fig. 2. Ray tracing for synthesizing elemental images in the real image field.

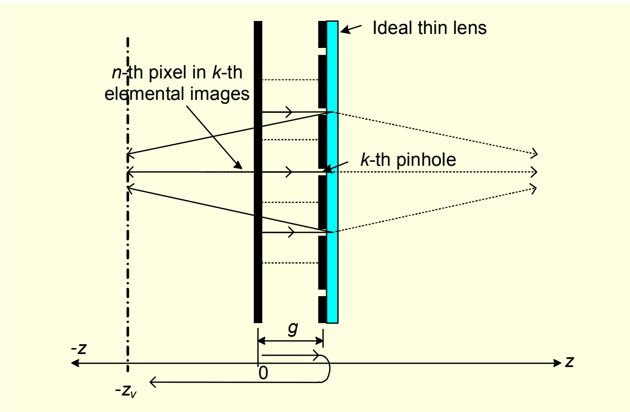

Fig. 3. Ray tracing for synthesizing elemental images in the virtual image field.

$$H_n^k(z_r) = kp\left(1 - \frac{z_r - g}{f}\right) - \frac{(z_r - g)nd}{g}. \tag{4}$$

The analysis of rays in the virtual image field is somewhat different from that in the real image field.

Next, we explain the elemental images of 3D object in the virtual image field. Figure 3 shows the scheme to synthesize the elemental images in the virtual image field of the proposed CPII system. A ray from the n-th pixel of the k-th elemental image to the thin lens passes through the real image field. However, after the ray starts from the thin lens, it travels in the $-z$ direction. If the ray reaches the distance $-z_v$ in the virtual image field, the transmission matrix of the ray is calculated by

$$T_v = \begin{bmatrix} 1 & g - z_v \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}. \tag{5}$$

Using (2) and (5), the height of each ray at distance z_v located in the virtual image field is given by

$$H_n^k(z) = kp\left(1 - \frac{g - z_v}{f}\right) - \frac{(g - z_v)nd}{g}. \tag{6}$$

To synthesize the final elemental images, we should calculate all n and k using (4) and (6) according to the distance. Here, when f is infinite, (6) becomes the analysis of the conventional PII without a large aperture thin lens.

3. Calculation of Viewing Angle

In integral imaging, the viewing angle is a major factor in the display system because an observer wants to see the 3D images without restriction on viewing positions. Basically, the viewing angle of the integral imaging is restricted because of the limited f-number of the lenslet array. When an observer sees the 3D images out of the viewing angle, image flipping occurs. Therefore, it is important to increase the viewing angle of integral imaging. Figure 4(a) is a diagram of the viewing angle in the conventional integral imaging. The viewing angle depends on the f-number of the lenslet array. This is given by

$$\theta_c = 2\arctan\left(\frac{p}{2g}\right). \tag{7}$$

On the other hand, the CPII system we propose can enhance the viewing angle of the 3D object in all directions. This can be calculated by considering the number of lenslets. The concept

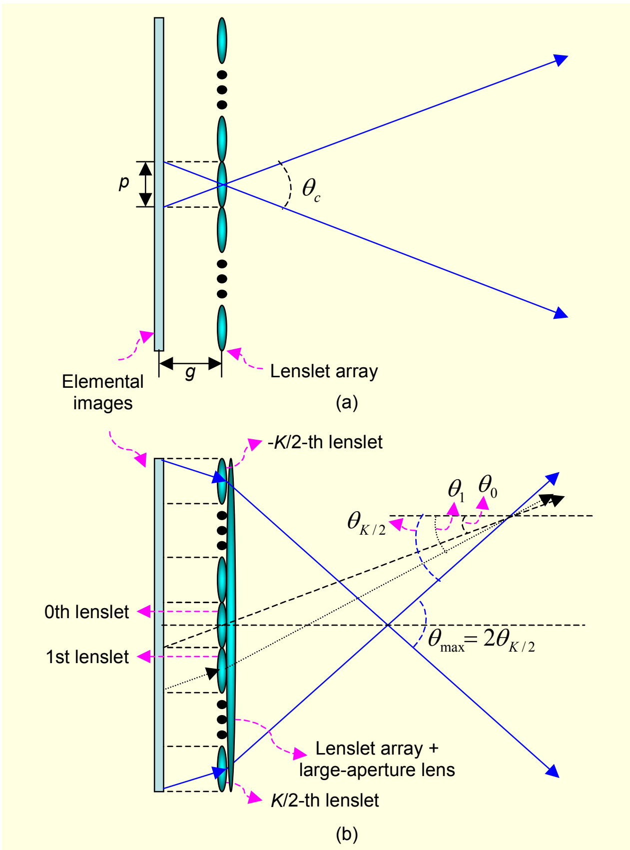

Fig. 4. Viewing angle in (a) the conventional system [8] and (b) the proposed system.

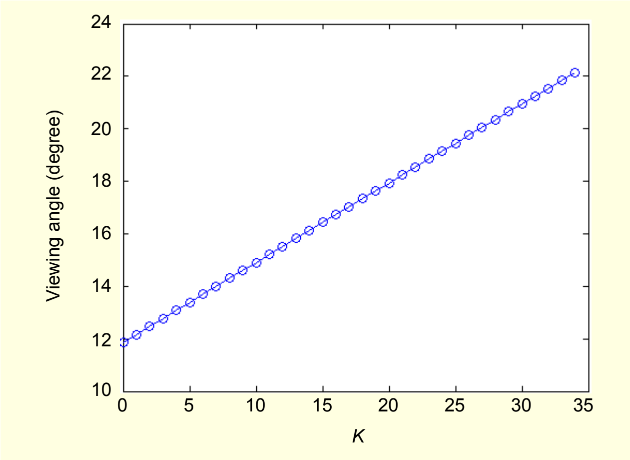

Fig. 5. Maximal viewing angle of the proposed system according to the K number.

of our viewing angle is shown in Fig. 4(b). When the number of lenslets K is odd, the viewing angle is chosen using two rays starting from the $-K/2$-th and $K/2$-th lenslets. This is the maximum viewing angle in the proposed system. The viewing angle θ_{max} can be derived as

$$\theta_{\max} = 2\arctan\left(\frac{p}{2g}+\frac{Kp}{2f}\right). \tag{8}$$

Figure 5 shows the calculated viewing angle using (8) when p=1.08 mm, g=5.2 mm, and f=200 mm. Here, the large K value provides the large viewing angle. However, the K value is limited by the size of the large aperture lens due to the fabrication difficulty. This tradeoff should be considered in designing the CPII system.

III. Experiments and Results

To demonstrate the proposed CPII system, preliminary experiments were performed using the optical setup shown in Fig. 6. A 2D LCD projector was used to display the elemental images. We used a lenslet array of 34×25 lenslets in which each lenslet is mapped with 30×30 pixels in the image projector. The diameter and focal length of the lenslets are p=1.08 mm and g=5.2 mm, respectively. The focal length of the large aperture lens is f=200 mm. The 3D object was composed of two character patterns as shown in Fig. 6. The Chinese character '光' was positioned at 30 mm in the virtual image field and the Chinese character '云' was positioned at 30 mm from the lenslet array in the real image field.

First, we synthesized the elemental images in the CPII system by using (4) and (6). The synthesized elemental images are shown in Fig. 7(b). For comparison, we present elemental images using the conventional PII in Fig. 7(a). We see that fewer elemental images were sampled for the character '光',

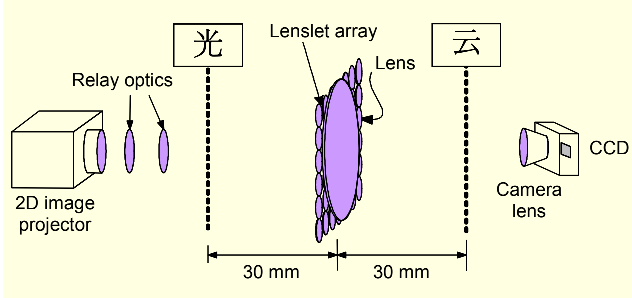

Fig. 6. Experimental setup.

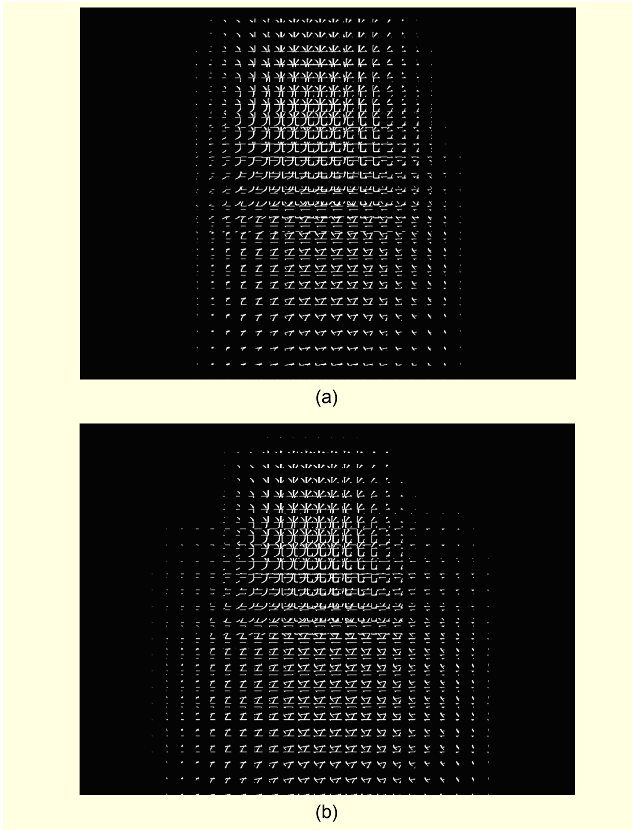

Fig. 7. Synthesized elemental images: (a) conventional PII and (b) proposed CPII.

and more elemental images were sampled for the character '云' in the proposed CPII system than in the conventional PII system. This is because the character '光' is picked up in the virtual image field and the character '云' is picked up in the real image field.

Next, we displayed the synthesized elemental images in the image projector shown in Fig. 6. Figure 8 shows the reconstructed images captured by the CCD camera in the real and virtual image fields when using the proposed CPII system. The image focused at the virtual image field is shown in Fig. 8(a), and the image focused at the real image field is shown in Fig. 8(b). Figure 9 shows the reconstructed images

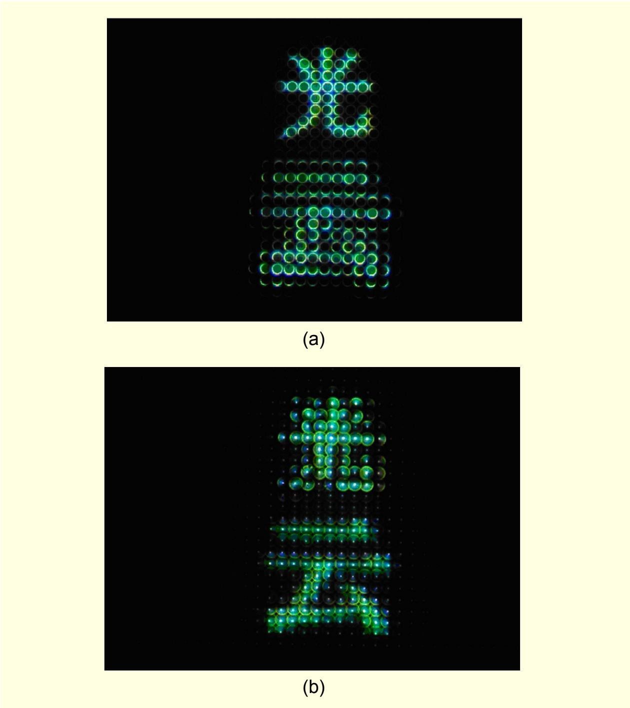

Fig. 8. (a) Focused image in the virtual image field and (b) focused image in the real image field using the proposed CPII system.

from different viewing angles. We observed the full '光' image within 6^o to the left and right in the conventional PII system as shown in Fig. 9(a). However, in the proposed CPII system, we observed images within 10^o to the left and right. Therefore, the measured viewing angle of the conventional PII system was approximately 12^o, and that of the proposed CPII system was approximately 20^o. Under the experimental conditions shown in Fig. 6, the theoretical viewing angles of the conventional and proposed systems were calculated to compare those of the optical experiments. From (7), (8), and Fig. 5, the theoretical viewing angles for the conventional PII system and the proposed CPII were calculated as approximately 12^o and 22^o, respectively. The calculated viewing angles agree well with the experimental results. From the experimental results, we can see that the proposed CPII system improves the viewing angle and displays 3D images simultaneously through the real and virtual image fields.

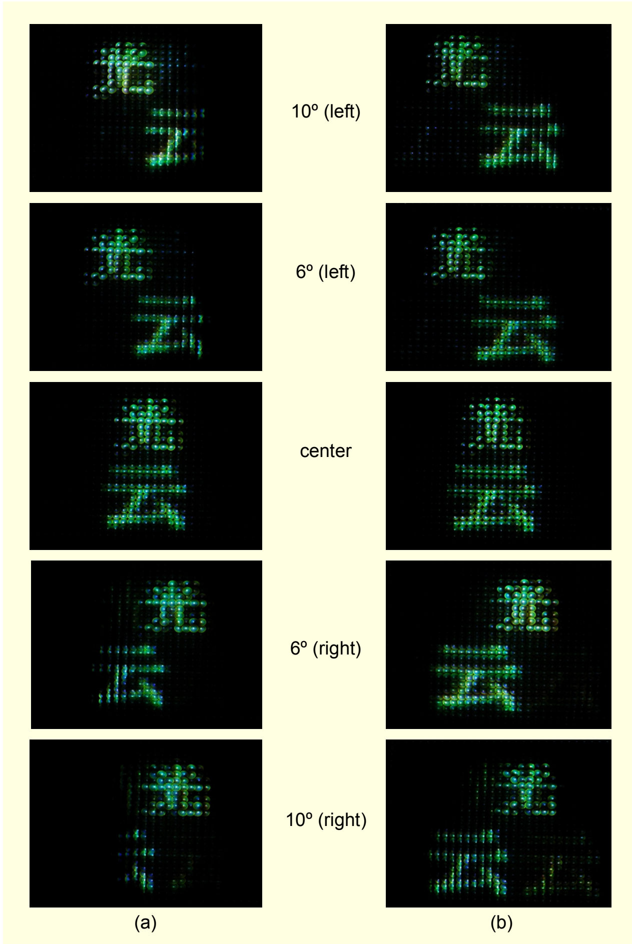

Fig. 9. Experimental results: (a) conventional PII system and (b) proposed CPII system.

IV. Conclusion

We proposed a CPII system which provides a curvature effect by using a large-aperture convex lens as an addition to the conventional PII system. The proposed system has a simple structure using of well-fabricated flat devices without any modification and provides a curvature effect by using a large-aperture convex lens. The experimental results demonstrate that the proposed system provides an improved viewing angle and can display 3D images simultaneously through the real and virtual image fields.

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