Viewing-angle-enhanced three-dimensional integral imaging using the combination of a lenticular lens sheet and a two-dimensional lens array

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ABSTRACT

Integral imaging is a promising way of three-dimensional display because it provides observers with full parallax and continuous view points without the use of glasses. However, the limitation on the viewing angle and the expressible depth should be overcome for integral imaging to be applied to real systems. There have been various methods such as using mechanical movements or polarization switching to improve the viewing angle of integral imaging. In this paper, we propose a viewing angle enhanced integral imaging system without any mechanical movement or polarization control. This new viewing angle enhanced system utilizes lenticular lens sheet to angularly multiplex the information emitted from each pixel. Thus each pixel can affect multiple lenses and the effective area of an elemental image is increased, which brings the enhanced viewing angle. The simulation result of the proposed system and the experimental results are provided.

Keywords: Integral imaging, three-dimensional display, lenticular lens sheet, viewing angle

1. INTRODUCTION

There has been a continuous endeavor of mankind to reconstruct or store objects visually throughout the history. It is from 20th century when enough scientific and engineering development is accomplished that human could research the method to display images three-dimensionally. Three-dimensional display system utilizing special glasses are available in various places such as theme parks. However, three-dimensional display systems using glasses can evoke headache when observers use them for a long time. Three-dimensional display systems without the use of glasses should be applied in practice for comfort of observers. Hologram, invented by Gabor in 1948, is the ideal three-dimensional display system. Nevertheless, far more researches are required to implement three-dimensional movies with hologram.[1]

Figure 1 shows the geometry to understand the basic concept of integral imaging. Integral imaging is a method of three-dimensional display proposed by Lippmann in 1908[2], and it is a promising way of three-dimensional display because it provides full parallax and does not require the observer to wear any special glasses. Integral imaging utilizes a lens array to form a three-dimensional image from two-dimensional elemental images. Lens array is also used in pick up

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process to record two-dimensional elemental images from given three-dimensional object. Though the integral imaging is proposed far earlier than hologram (it was called integral photography at that time), it was not popular as hologram because the display medium for two-dimensional elemental images was film and the production of the lens array was not easy. Integral imaging has drawn attentions of scholars and engineers recently with the development of two-dimensional display media and computers[3-5]. Presently any PC monitor can be used as the display medium of two-dimensional elemental images. Integral imaging makes economical implementation of three-dimensional movie system possible without the use of special glasses, and computers can be used to generate elemental images without physical pickup process.

However, integral imaging has limited expressible depth range because the integration of three-dimensional image far from the central depth plane introduces distortions to the integrated three-dimensional image[6]. Also the viewing angle is limited in integral imaging system because each elemental lens possesses corresponding elemental image area which has the same area of the elemental lens[7]. Enhancing the expressible depth range and the viewing angle is crucial to apply integral imaging in practice, and there have been a number of researches to enhance them. Mainly researches are focused on enhancing the viewing angle of integral imaging using mechanical movement or polarization switching[8,9]. However, mechanical movement makes the implementation of the system difficult and polarization switching brings low efficiency of light. In this paper, we propose an integral imaging system with enhanced viewing angle without mechanical movement or polarization switching and Fig. 2 shows the geometry of the proposed system.

![Figure 2. Basic concept of the proposed system](image)

Lenticular lens sheet is used for enlarging the area of elemental image corresponding to an elemental lens. In conventional integral imaging system, the pixel under a certain elemental lens contains the information only for the elemental lens above it because a pixel gives same information in all directions. However, if a pixel can give different information in different directions, a pixel can have information for not only the elemental lens above it, but also the elemental lenses next to it. Thus the effective elemental image area can be increased from the viewpoint of elemental lens. Detailed principles of the proposed system and the experimental results are given in the following.

2. THE VIEWING-ANGLE-ENHANCED THREE-DIMENSIONAL INTEGRAL IMAGING SYSTEM USING THE COMBINATION OF A LENTICULAR LENS SHEET AND A TWO-DIMENSIONAL LENS ARRAY

In conventional integral imaging system, each pixel is observed through the elemental lens above it. Thus each elemental lens has the elemental image area which has the same area as the elemental lens, and the viewing angle of the system is determined to be
\[ \theta = 2 \arctan \left( \frac{\phi}{2g} \right), \tag{1} \]

where \( \phi \) is the pitch of elemental lens and \( g \) is the gap between the elemental lens and the display device. Figure 3 shows the geometry for the viewing angle analysis of a conventional integral imaging system.

In the proposed system, several pixels are under one lenticular lens. A lenticular lens takes the role of determining which pixel is to be displayed according the observing angle as in Fig. 4. By carefully designing, a lenticular lens can work as a pixel which displays different information to different elemental lens. In Fig. 4, the group of pixels named ‘C’ displays information for the elemental lens above it, while the group named ‘L’ displays information for the elemental lens left to it and the group named ‘R’ displays information for the elemental lens right to it. Therefore it can be considered that each elemental lens has elemental image area which is bigger than the area of the elemental lens, in this case, triple of the area of the elemental lens. The proportional value of elemental image area to the area of the elemental lens can be increased if a lenticular lens can display information for more elemental lenses.
Since each elemental lens has effectively the elemental image area which is triple of the area of the elemental lens, the viewing angle can be calculated to be

\[ \theta = 2 \arctan \left( \frac{3 \phi}{2g} \right). \]  

(2)

By comparing Eqs. (1) and (2), it can be noticed that the viewing angle of the proposed system is about three times the viewing angle of the conventional system. The design scheme of the elemental image will be explained in the following.

### 3. ELEMENTAL IMAGE DESIGN OF THE VIEWING-ANGLE-ENHANCED THREE-DIMENSIONAL INTEGRAL IMAGING SYSTEM USING THE COMBINATION OF A LENTICULAR LENS AND A TWO-DIMENSIONAL LENS ARRAY

![Figure 5. Geometry for the understanding of computer generated elemental image](image)

Physical pickup of the elemental image can introduce pseudoscopic image problem and aberration. With the development of computer, elemental image generation using computer was proposed[10] and it has no pseudoscopic image problem or aberration. Figure 5 shows geometry for understanding the generation of elemental image by computer, where \( P_O \) is the coordinate of the object point which we are interested in, \( P_E \) is the elemental image point of \( P_O \) through \( q \)th elemental lens and \( C_q \) is the coordinate of the center of \( q \)th elemental lens. In Fig. 5, only horizontal components are considered for simplicity. The goal of computer generated elemental image is that calculating the coordinates of every \( P_E \) for each object point \( P_O \). The elemental image point for object point through every elemental lens should be calculated and be discarded if the elemental image point is out of the elemental image area of the elemental lens under consideration. Since the value of \( z_o \) is known before the calculation, simple proportional relation can be applied to find the value of \( x_e \). \( x_e \) is calculated to be

\[ x_e = q\phi + (q\phi - x_o) \frac{g}{z_o}, \]  

(3)

and the resultant value should satisfy the following condition

\[ q\phi - \frac{\phi}{2} \leq x_e \leq q\phi + \frac{\phi}{2}. \]  

(4)
for it to be located in correct elemental image area. Elemental image of the object point can be produced by gathering every elemental image point that satisfies Eqs. (3) and (4), and gathering every elemental image of the object point produces the elemental image of the object in conventional integral imaging system.

To generate the elemental image of the proposed system, the above equations should be applied with proper modification and more calculations are demanded for consideration of the effect of lenticular lens sheet. Equation (3) is enough for finding the location of elemental image point, but Eq. (4) should be modified since elemental image area for each elemental lens is enlarged. When one lenticular lens takes charge of three elemental lenses, Eq. (4) should be

$$q\phi - \frac{3\phi}{2} \leq x \leq q\phi + \frac{3\phi}{2}. \quad (5)$$

![Diagram](image_url)

Figure 6. Geometry to determine which pixels correspond to the elemental lens under consideration.

Equations (3) and (5) are enough to find the information to be displayed by each lenticular lens, and there will be at most three different information assigned to each lenticular lens. Next it should be determined which information among three different information is to be displayed by each pixel under the lenticular lens. This can be done by calculating through which elemental lens each pixel will be observed. Figure 6 shows the concept of this calculation, where $c_l$ is the distance between the display device and the optical center of lenticular lens, $C_{ql}$ is the coordinate of the center of $q_l^{th}$ lenticular lens, $\phi_l$ is the pitch of lenticular lens, $R$ and $L$ are respectively the coordinate of right border and left border of $q_e^{th}$ elemental lens, $q_e$ is the pitch of elemental lens and $b_r$ and $b_l$ are respectively the address of rightmost and leftmost pixels correspond to the elemental lens under consideration. When first pixel is located where the x-coordinate is 0, $b_r$ and $b_l$ can be calculated as

$$b_r = \frac{q_l\phi_l + \left(q_l\phi_l - q_e\phi_e + \frac{\phi_e}{2}\right) c_l}{p}, \quad b_l = \frac{q_l\phi_l + \left(q_l\phi_l - q_e\phi_e - \frac{\phi_e}{2}\right) c_l}{p}. \quad (6)$$

where $p$ is the pixel pitch of display device and $\lceil n \rceil$ represents the smallest integer bigger than $n$. Now the information through the elemental lens under consideration is located from $b_l$ to $b_r$. Repeating this process for three elemental lens assigned to each lenticular lens completes the elemental image design for the proposed system.
4. EXPERIMENTAL RESULTS

We performed an experiment that will show the enhanced viewing angle of proposed system. The experimental parameters are represented in Table 1.

Table 1. Experimental parameters

<table>
<thead>
<tr>
<th>Setup</th>
<th>Specifications</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenticular lens sheet</td>
<td>LPI (lines per inch)</td>
<td>73.70</td>
</tr>
<tr>
<td></td>
<td>Focal length</td>
<td>450 μm</td>
</tr>
<tr>
<td></td>
<td>Distance between the back side</td>
<td>410 μm</td>
</tr>
<tr>
<td></td>
<td>and the principal point</td>
<td></td>
</tr>
<tr>
<td>SLM</td>
<td>Pixel pitch</td>
<td>36 μm</td>
</tr>
<tr>
<td>Lens array</td>
<td>Focal length</td>
<td>30 mm</td>
</tr>
<tr>
<td></td>
<td>Number of elemental lenses</td>
<td>5(H) × 5(V)</td>
</tr>
<tr>
<td></td>
<td>Pitch of elemental lens</td>
<td>5 mm</td>
</tr>
<tr>
<td>Object</td>
<td>Depth</td>
<td>60 mm (virtual)</td>
</tr>
</tbody>
</table>

The designed elemental image for the proposed system with given setup and the elemental image for the conventional integral imaging are shown in Fig. 7. A picture of Saturn is used as the object. When we put the lenticular lens sheet on the SLM, the elemental image changes as the observing position changes as in Fig. 8. Figure 9 shows the computer-generated elemental images which have different spatial relationship between elemental lenses and corresponding elemental image area. In Fig. 9 (a), elemental image area is assigned to the elemental lens left to it, while elemental image area is assigned to the elemental lens right to it in Fig. 9 (c). Thus if the elemental image is correctly designed and the lenticular lens sheet is working in intended way, Figs. 8 and 9 should look same except for horizontal resolution. By comparing Figs. 8 and 9, we can conclude that the elemental image design is successful.

Figure 7. Elemental images for the proposed system and the conventional system.

(a) elemental image for the proposed system                   (b) elemental image for the conventional system
Figure 8. The elemental image for the proposed system observed through a lenticular lens sheet.

Figure 9. Elemental images that have different spatial relationship between elemental lenses and elemental image areas.

Figure 10. Integrated image by the proposed system observed from various directions
(a) observed from left  (b) observed from center  (c) observed from right
(d) observed from 5˚ down  (e) observed from 9˚ up

(a) when each elemental image area corresponds to elemental lens left to it
(b) when each elemental image area corresponds to elemental lens above it (conventional case)
(c) when each elemental image area corresponds to elemental lens right to it

Figure 9. Elemental images that have different spatial relationship between elemental lenses and elemental image areas.
The integrated images by the proposed system are shown in Fig. 10, and the integrated images by the conventional system are shown in Fig. 11. As expected, images in Fig. 10 are worse in resolution than images in Fig. 11. However, the viewing angle is significantly increased in the proposed system. In the conventional system, lateral viewing angle is only 11˚. Figure 11 (c) and (f) show the flipping effect, which occurs when a pixel is observed through an elemental lens that is not above it. And the images in Fig. 11 (d) and (g) show severe distortion, while Fig. 10 (b) and (c) are still displaying correct integrated image under the same condition. Nevertheless, vertical viewing angle is almost the same since the lenticular lens does not affect light propagation in vertical direction.

Figure 11. Integrated image by the conventional system observed from various directions
5. CONCLUSION

We proposed a viewing-angle-enhanced three-dimensional integral imaging using the combination of a lenticular lens sheet and a two-dimensional lens array. The experimental results that confirm the enhanced viewing angle of the proposed system is provided.

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