Integral imaging without image distortion using micro-lens arrays with different specifications

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Abstract. We propose an integral imaging in which the micro-lens array
(MLA) in the pickup process called MLA 1 and the micro-lens array in the
display process called MLA 2 have different specifications. The elemental
image array called EIA 1 is captured through MLA 1 in the pickup process.
We deduce a pixel mapping algorithm including virtual display and virtual
pickup processes to generate the elemental image array called EIA 2
which is picked up by MLA 2. The three-dimensional images reconstructed
by EIA 2 and MLA 2 do not suffer any image scaling and distortions. The
experimental results demonstrate the correctness of our theoretical analy-
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1 Introduction

Integral imaging (II), which was originally called integral
photography, is one of the most attractive techniques in
the field of three-dimensional (3-D) displays. It has many
advantages over other 3-D display techniques. For example,

parameters of micro-lenses are entirely different for the
pickup process. However, stereo matching is needed to
detect the disparity between two or more EIs and the quality
of the generated 3-D image will be degraded. The scaling
was also achieved by controlling the spatial ray sampling
rate of EIA in the pickup process and a digital magnifica-
tion method using interpolation theory was proposed to
increase the spatial ray sampling. The intermediate-view
reconstruction technique using the same interpolation theory
was used to increase the number of EIs (Ref. [20]). But the
parameters of the micro-lens are not changed in these tech-
niques. Smart pixel mapping algorithm is proposed by
Martínez-Corral et al. to resolve the pseudoscopic problem
of the reconstructed 3-D image, which is also resolved by
Jung et al. recently.

In this paper, we propose an II without image distortion
using MLAs with different specifications in the pickup and
display processes. The deduced pixel mapping algorithm not
only resolves the pseudoscopic problem, but also generates
the EIA with different lens specifications, and the recon-
structed 3-D images do not have any distortions.

2 Principle of the Proposed II

Figure 1 shows the schematic of the proposed II which has
different specifications of MLAs in the pickup and display
processes. In the pickup process, as shown in Fig. 1A, the
MLA and the EIA are called MLA 1 and EIA 1, respectively.
The pitch and the focal length of MLA 1 are \( p_1 \) and \( f_1 \),
respectively, and MLA 1 contains \( M_1 \times N_1 \) micro-lenses.
EIA 1 is recorded on the rear focal plane of MLA 1 and
the pitch of EIA 1 is the same with that of MLA 1. In
the display process, as shown in Fig. 1B, the MLA and
the EIA are called MLA 2 and EIA 2, respectively. The
pitch and the focal length of MLA 2 are \( p_2 \) and \( f_2 \), respec-
tively, and MLA 2 contains \( M_2 \times N_2 \) micro-lenses. EIA 2
generated by the pixel mapping algorithm has different spec-
fications from EIA 1, and the 3-D image reconstructed by
EIA 2 and MLA 2 maintains the original size and location of
the 3-D object without any distortions.
Figure 2 shows the schematic of the proposed pixel mapping algorithm which includes the virtual display process and the virtual pickup process. Since the virtual display process and the virtual pickup process form the standard configuration of II, EIA 1 and MLA 1 reconstruct a 3-D image that maintains the original size and location of the 3-D object, but with the reversed depth. But the pseudoscopic problem can be resolved by the pixel mapping algorithm because the combination of the virtual display process and the virtual pickup process is a modified version of the two-step pickup process. In the virtual pickup process, MLA 2, which is the same as the one used in the display process in Fig. 1(b) and which has different specifications from MLA 1, picks up the depth-reversed 3-D image. The distance between MLA 1 and MLA 2 is $L$. EIA 2 that has different specifications from EIA 1 can be obtained on the rear focal plane of MLA 2, and EIA 2 and MLA 2 have the same pitch of $p_2$. The resolutions of EIs in EIA 1 and EIA 2 are both $r \times r$.

In practice, the virtual display and virtual pickup processes are carried out by mapping all the pixels in EIA 1 to EIA 2 through the following mathematical relationships. As shown in Fig. 2 in the $m'$th row and the $n'$th line EI of EIA 1, a pixel in the $i'$th row and the $j'$th line denoted as $I_1(m, n)_{i,j}$. The rays emitted from the pixel $I_1(m, n)_{i,j}$ are refracted by the micro-lenses in MLA 1 and MLA 2, and then arrive at the $i'$th row and the $j'$th line pixel of the $m'$th row and the $n'$th line EI in EIA 2. The pixel in EIA 2 is denoted as $I_2(m', n')_{i',j'}$. EIA 2 can be generated by using the following mathematical relationships:

$$I_2(m', n')_{i',j'} = I_1(m, n)_{i,j}. \quad (1)$$

$$m' = \text{round} \left[ m + 1 + \frac{L}{f_2 r}(i - r) \right]. \quad (2)$$

$$n' = \text{round} \left[ n + 1 + \frac{L}{f_2 r}(j - r) \right]. \quad (3)$$

$$i' = \text{round} \left[ r/2 + \frac{p_2 f_1}{p_1 f_2} \left( \frac{r}{2} - i \right) \right] \quad (4)$$

$$j' = \text{round} \left[ r/2 + \frac{p_2 f_1}{p_1 f_2} \left( \frac{r}{2} - j \right) \right] \quad (5)$$

where the function round $(\cdot)$ rounds a number to the nearest integer. When $i$ or $j$ is bigger than $r$, the pixel should be abandoned to eliminate the overlapping between adjacent EIs. In this way, in loop $m$ from 1 to $M_1$, $n$ from 1 to $N_1$, $i$ from 1 to $r$, and $j$ from 1 to $r$, all the pixels in EIA 1 are mapped to the rear focal plane of MLA 2, and an EIA 2 that has different specifications from EIA 1 is generated.

The distance $L$ between MLA 1 and MLA 2 determines the depth of the reconstructed 3-D image. Assuming that in the pickup process, the distance between the 3-D object and MLA 1 is $l_o$, the depth of the reconstructed 3-D image in the display process is...
When \( l_a = L \), the 3-D image will be displayed on the MLA 2 plane, and when \( l_a > L \) or \( l_a < L \), the 3-D image will be displayed behind or in front of the MLA 2 plane.

When the light rays emitted from the pixel in the adjacent EI in EIA 1 are refracted by MLA 1 and MLA 2 and arrive at EIA 2, the crosstalk pixel is produced, as shown in Fig. 3. So the pitches and the focal lengths of MLA 1 and MLA 2 should satisfy Eq. (6) to avoid the crosstalk pixel

\[
\frac{p_1}{f_1} \geq \frac{p_2}{f_2}.
\]

(7)

The uninformed pixel will be caused when pixels in EIA 2 have no corresponding pixels in EIA 1, as shown in Fig. 4. So the numbers of EIs in EIA 1 and EIA 2, \( M_1 \times N_1 \) and \( M_2 \times N_2 \), should satisfy Eqs. (8) and (9) to avoid the uninformed pixels

\[
M_1 \geq \text{ceil} \left( \frac{p_2 M_2 f_2 + p_2 L}{p_1 f_2} \right),
\]

(8)

\[
N_1 \geq \text{ceil} \left( \frac{p_2 N_2 f_2 + p_2 L}{p_1 f_2} \right),
\]

(9)

where the function \( \text{ceil}(\cdot) \) rounds a number to the largest integer.

3 Experiments and Results

In this experiment, a 3-D scene which consists of three plane images with different depths is built up as shown in Fig. 5. A camera array is used to simulate MLA 1. The Z-axis shows the distances between the characters and the camera arrays, and they are 60, 100, and 150 mm, respectively. Three experiments using the proposed II, conventional II without scaling, and straightforward scaling II in Ref. 11 are carried out. The specifications of MLA 1 and MLA 2 are listed in Table 1 in which the parameters of MLA 1 and MLA 2 in the proposed II satisfy the relationships in Eqs. (6)–(9). Three EIs 2 obtained using the three II methods are shown in Figs. 6(a), 6(b), and 6(c), respectively.

The depth-based computational II reconstruction is implemented to reveal explicitly the cross sections of the reconstructed 3-D images along the longitudinal direction, so that the longitudinal magnification of the 3-D image can be readily determined. Since the distance \( L \) between MLA 1 and MLA 2 is 100 mm, the reconstructed undistorted 3-D images should be located at the depths of \(-50, 0, \) and 40 mm, respectively. As shown in Figs. 7(a) and 7(b), the 3-D images reconstructed by our proposed II have the same depths without the pseudoscopic problem as the ones reconstructed by the conventional II and their longitudinal magnifications are both 1. However, using the straightforward scaling II as shown in Fig. 7(c), the reconstructed 3-D images have the longitudinal magnification of \( f_2/f_1 = 0.86 \).

![Fig. 4](https://example.com/f4.png)

**Fig. 4** Comparisons between the numbers of EIs in EIs 1 and 2.

![Fig. 5](https://example.com/f5.png)

**Fig. 5** Three-dimensional (3-D) scene in the experiments.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Specifications of MLAs 1 and 2 in the experiments.</th>
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<tbody>
<tr>
<td>Method</td>
<td>( p_1 ) (mm) ( f_1 ) (mm) ( p_2 ) (mm) ( f_2 ) (mm) ( L ) (mm) ( M_1 \times N_1 ) ( M_2 \times N_2 )</td>
</tr>
<tr>
<td>Proposed II</td>
<td>1.25</td>
</tr>
<tr>
<td>Conventional II without scaling</td>
<td>1.25</td>
</tr>
<tr>
<td>Straightforward scaling II</td>
<td>1.25</td>
</tr>
</tbody>
</table>

When \( l_a = L \), the 3-D image will be displayed on the MLA 2 plane, and when \( l_a > L \) or \( l_a < L \), the 3-D image will be displayed behind or in front of the MLA 2 plane.

When the light rays emitted from the pixel in the adjacent EI in EIA 1 are refracted by MLA 1 and MLA 2 and arrive at EIA 2, the crosstalk pixel is produced, as shown in Fig. 3. So the pitches and the focal lengths of MLA 1 and MLA 2 should satisfy Eq. (6) to avoid the crosstalk pixel

\[
\frac{p_1}{f_1} \geq \frac{p_2}{f_2}.
\]
The optical II 3-D display experiments are carried out to verify the lateral magnifications of the reconstructed 3-D images. Since the total resolution of each EIA 2 is pretty high, a high-resolution color printer, EPSON STYLUS PHOTO 1390, is used to print three EIAs 2. Three MLAs 2 are used to match with the three printed EIAs 2 and three II 3-D pictures are obtained as shown in Fig. 8. A ruler is used to measure the lateral size of the reconstructed 3-D images. As shown in Figs. 8(a) and 8(b), the lateral sizes of the characters “II”s reconstructed by our proposed II and the conventional II without scaling are both 67.5 mm. However, using the straightforward scaling II as shown in Fig. 8(c), the lateral size of the reconstructed characters “II” is 43.5 mm. So the lateral magnifications of the proposed II are 1 and the lateral magnification of the straightforward scaling II is about $p_2/p_1 = 0.644$.

4 Conclusions

In this paper, we propose an II in which MLA 1 in the pickup process and MLA 2 in the display process have different specifications. The pixel mapping algorithm that functions as a converter to transmit the pixels from EIA 1 to EIA 2 not only resolves the pseudoscopic problem but also generates the EIA with different lens specifications. We also deduce the mathematical relationship between EIAs 1 and 2, and the relationships between the parameters of EIAs 1 and 2, and between MLAs 1 and 2. As long as the parameters of MLA 1 and MLA 2 satisfy the relationships in Eqs. (7)–(9), the parameters of MLA 2 and EIA 2 can be selected arbitrarily, hence different EIAs 2 can be generated from EIA 1 for different II 3-D display systems. The experimental results demonstrate that the reconstructed 3-D images in the proposed II maintain the original lateral and longitudinal sizes of the 3-D object without any scaling and distortion. The proposed II could be an ideal candidate for 3-D television broadcasting in the future.
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References

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