Point light source display with a large viewing angle using multiple illumination sources

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Abstract. A point light source (PLS) display with enhanced viewing angle (VA) is proposed. The maximum VA of a conventional PLS display is equal to the propagation angle of the PLS, so a light-source array (3 × 3) was used to enlarge the propagation angle of the PLS in the horizontal and vertical directions. The number of converging elemental image points increases due to the large propagation angle of the PLS; thus, the VA of the integrated point was enhanced. From the experimental results, the VA of the proposed method was 2.6 times larger than the maximum VA of a conventional PLS display.

1 Introduction
The point light source (PLS) display is one kind of integral-imaging display.1–4 Its advantages include full-parallax, real-time, and continuous viewpoints. The depth of the integral imaging display is short.5 The most important advantage of a PLS display is that there is no restriction on object depth.5 Some methods that are based on the PLS are the three-dimensional (3-D) and two-dimensional (2-D) convertible integral-imaging systems.6–9 Limitations of the PLS display include those regarding the VA and the resolution. Thus, we suggest new methods to enhance the VA and the resolution.

Erdenebat et al.10 enhanced the VA by 360 deg using a high-speed rotating mirror. An integral-floating image was projected onto a mirror on a high-speed motor to enhance the horizontal VA. This method can display a 360-deg integral-floating image, but the vertical VA is the same as that of a conventional display and requires a mechanical aspect. Kim et al.11 proposed enhancing the resolution and the VA of an integral-imaging system using an electrically movable pinhole array. They used two displays; the first displayed the elemental image (EI) and the second display was used for the electrically movable pinhole arrays. This method does not require any movable parts but enhances only the horizontal VA.

Park et al.12 proposed the use of time-multiplexed double light sources to enhance the VA in the horizontal direction. Noncollimated illumination and converging illumination can enhance both the horizontal and vertical VAs in the real-image mode and the virtual-image mode, respectively. This method uses time-multiplexing illumination, and the VA is twice as large as that of the conventional method. Alam et al.13 proposed using a directional projection and EI resizing method. This method requires several sets of EIs for the each different direction. They changed the positions of the projector and the collimating lens in each direction.

Cho et al.14 proposed the use of a 5 × 5 light-emitting diode (LED) array to enhance the VA. To convert 3-D to 2-D, they used a display technique with a diffuser. The method did not require a collimating lens, but they used a special LED that produced parallel light, and it is difficult to obtain this LED (IWVUW3A2T).

This paper presents a viewing-angle (VA) enhancement method, which uses nine LEDs to enlarge the PLS light field. The feasibility of the method was experimentally verified.

2 Limitation of Viewing Angle
A PLS display consists of a light source, a collimating lens, a lens array, and a spatial light modulator (SLM) for a 2-D transparent display (Fig. 1). The light source S is at the focal point of the collimating lens, so all of the incident rays refract through the collimating lens and travel parallel to the principal axis. The lens array collects the parallel beams at the focal point of each elemental lens so that it looks like a PLS array. That is, many light sources are on the focal plane of the lens array, so it is called a PLS array.12,13 The distance between the SLM and the lens array can be expressed as $g = \frac{2f}{f}$, because the light fields of the neighboring PLSs do not intersect and overlap. The SLM modulates the incident rays from the PLSs with the EI.

In previous studies,2,15 the VA was given by a simple geometric calculation

$$VA = 2 \cdot \arctan \left( \frac{P_L}{2f} \right). \quad (1)$$

where $f$ is the focal length of the lens array and $P_L$ is the pitch of the elemental lens. The light rays from the PLSs passing through the SLM then converge at a point that is a 3-D integrated point.2 For example, the integrated points $P_1$ and $P_2$ appear at the converging point of five EI points and four EI points, respectively. The light rays from the PLSs are integrated into 3-D images, so it is called a PLS...
For example, the elemental lenses $L_{10}$, $L_{11}$, and $L_{12}$ collect the rays that pass the collimating lens from the light sources $S_1$, $S_2$, and $S_3$ at the center of the elemental lens, $L_{11}$, respectively (Fig. 2). The two additional fields from the sources $S_1$ and $S_3$ enlarge the propagation angle of the single PLS, so the propagation angle of the PLS for the proposed method is larger than the propagation angle of the PLS for the conventional method.

Figure 2 shows the formation of the integrated points $P_1$ and $P_2$. In a conventional PLS display, the integrated point $P_1$ appears at a converging point of the five EI points that are illustrated as lines, and a VA of the point $P_1$ is $VA_{C1}$ (Fig. 2). In the proposed method, point $P_1$ appears at the converging point of the nine EI points, illustrated by five solid lines and four dashed lines, and the VA is $VA_{P1}$. Those additional four EI points increase the VA of the integrated point, $P_1$.

When the specifications for the collimating lens and the lens array are given, it is possible to determine the distance of a light source from the principal axis of the collimating lens, the maximum VA of the proposed method, and the distance between the lens array and the SLM. The light fields of neighboring PLSs do not intersect or overlap, so the distance between the lens array and the SLM is given by

$$g = \frac{4f}{3}.$$  

Because the three parts of one PLS do not overlap each other and the rays converge at the center of the elemental lens to create the PLS, the distance of the light sources from the principal axis of the collimating lens is given by

$$l_s = \frac{(n - 1)f_{CL}}{2f} \cdot P_L,$$  

where $f_{CL}$ is the focal length of the collimating lens and $n$ is the number of light sources, where $n = 3$ (Fig. 2). When the lens array is close to the collimating lens, a single elemental lens collects three parallel beams that travel in three different directions. For example, the elemental lenses $L_{10}$ and $L_{13}$ collect the rays of just two light sources in Fig. 2, whereby one elemental lens must collect the rays from three light sources.

The maximum VA of the proposed method is given by

$$VA_{max} = 2 \cdot \arctan \left( n \cdot \frac{P_L}{2f} \right).$$

Equation (4) can determine the proportion angle of the PLS for the proposed method. From Eqs. (1) and (4), the proportion angle of PLS is enhanced if the number of light sources $n$ increases.

### 4 Experimental Results and Discussion

In the experiment, the pitch of the elemental lens was $P_L = 1$ mm, and the focal lengths of the lens array and the collimating lens were $f = 3.3$ mm and $f_{CL} = 56.8$ mm, respectively. An SLM of $1024 \times 760$-pixel resolution and a 0.036-mm pitch were used.

We calculated the maximum VA of the proposed method and the distance between light sources using Eqs. (3) and (4) with differing numbers of light sources (Table 1). When the light source array was $2 \times 2$, the VA was 1.9 times larger than the conventional PLS (Table 1). However, this was not sufficient. When the light source array is $4 \times 4$, the distance between the two farthest sources in the vertical direction was 56 mm, which was greater than the diameter of our collimating lens. Thus, we used a $3 \times 3$ light source array in the experiment.
The experiments used two objects from the lens array: “T” and “D” that were located 10 and 20 mm from the SLM, respectively. Figure 5 shows two sets of EIs for the conventional method and proposed method. From Figs. 5(a) and 5(b), the numbers of EIs are larger than with the conventional method. Thus, the extra EIs increased the VA.

The experimental results of the proposed method are shown in Fig. 6 and the movie versions are shown in Video 1. According to the experimental result, the VA of the proposed method is 44 deg. The maximum VA of the conventional PLS display was calculated as 17.2 deg, with Eq. (1), and the maximum VA of the proposed method is theoretically 48.8 deg, by Eq. (4). From the experimental results, the

<table>
<thead>
<tr>
<th>Light sources (n x n)</th>
<th>VA max (deg)</th>
<th>l_s (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 1</td>
<td>17.2</td>
<td>0</td>
</tr>
<tr>
<td>2 x 2</td>
<td>33.7</td>
<td>9.3</td>
</tr>
<tr>
<td>3 x 3</td>
<td>48.8</td>
<td>18.7</td>
</tr>
<tr>
<td>4 x 4</td>
<td>62.4</td>
<td>28</td>
</tr>
<tr>
<td>5 x 5</td>
<td>72.2</td>
<td>37.4</td>
</tr>
</tbody>
</table>
duplicated “T” and “D” are evident when the VAs are at left 10 deg and right 10 deg, respectively, because of the overlapped fields in Fig. 4(d). The one point of EI is illuminated by the overlapped light fields at left 10 deg and right 10 deg, so the 3-D images are duplicates. The light fields overlap because of Petzval curvature [Fig. 4(d)]. To eliminate the duplicated image, we can use a head-tracking and multiplexing LED, which is turned on and off selectively depending on the viewer’s position.

Figure 7 shows the experimental result when one source is on. It is like a conventional PLS display. In Figs. 7(b) and 7(f), the objects “T” and “D” disappear at left 10 deg and right 10 deg, respectively. In Figs. 7(a) and 7(g), the objects “T” and “D” disappear at left 11 deg and right 11 deg, so the VA is 20 deg when one source is on. From Figs. 6 and 7, the additional light sources enhance the VA.

5 Conclusions
In this paper, we proposed a PLS display with a larger VA. Our new method uses just one set of EIs, so it differs from other methods that use many sets of EIs. LEDs were used in this study to enhance the propagation angle of the PLS. From the experimental results, the VA was 2.6 times larger than that of a conventional PLS display of the same configuration, when the light source array was 3 × 3. If the LED array is increased to n × n, the VA will be enhanced further (Table 1). If the lens array used is without aberration, the proposed method does not display the duplicated 3-D image. The VA can be enlarged if more LEDs, which are inexpensive and controllable, are used. In further work, we will examine using switching LEDs to eliminate the duplicated image.

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References

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