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. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.56.5.053113]

1 Introduction

The point light source (PLS) display is one kind of integral-imaging display.[1–6] Its advantages include full-parallax, real-time, and continuous viewpoints. The depth of the integral imaging display is short.[2] The most important advantage of a PLS display is that there is no restriction on object depth.[7] 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.[12,14] The distance between the SLM and the lens array can be expressed as $g = 2f$, 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

$$\text{VA} = 2 \cdot \arctan\left(\frac{P_L}{2f}\right), \qquad (1)$$

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

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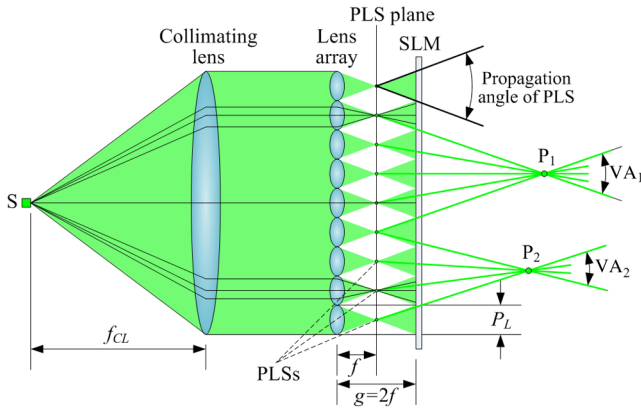
Fig. 1 Structure of a PLS display.

display.[11] From Fig. 1, the VAs of P_1 and P_2 are different; however, Eq. (1) determines the maximum VA,[16] which is equal to the propagation angle of the PLS. The VA of the PLS display is enhanced if the propagation angle of the PLS is enlarged.

3 Proposed Method

A light-source array (3×3) was used to enlarge the propagation angle of the PLS in the horizontal and vertical directions. Figure 2 shows the structure of the proposed method with three light sources along the vertical axis. The incident rays from two additional light sources S_1 and S_3, which are at a distance l_s from the principal axis of the collimating lens, are refracted with the collimating lens and travel parallel to the angle of incidence α (Fig. 2). The elemental lens refracts three parallel beams from the up, center, and down light sources to the focal points of the down, center, and up elemental lenses, respectively; thus, one PLS consists of three light fields. 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
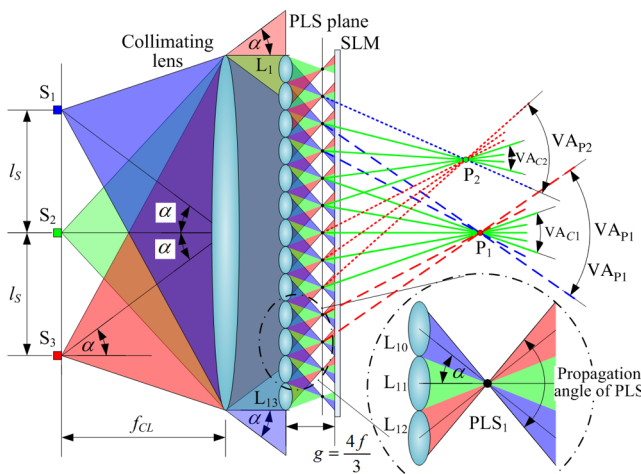

Fig. 2 Schematic configuration of the proposed method.

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

$$g = \frac{4f}{3}. \tag{2}$$

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

$$l_s = \frac{(n-1)f_{CL}}{2f} \cdot P_L, \tag{3}$$

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_1 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

$$VA_{max} = 2 \cdot \arctan\left(n \cdot \frac{P_L}{2f}\right). \tag{4}$$

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 1024×760-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 2×2, the VA was 1.9 times larger than the conventional PLS (Table 1). However, this was not sufficient. When the light source array is 4×4, 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 3×3 light source array in the experiment.

Table 1 Calculation of the maximum VA and the distance between light sources.

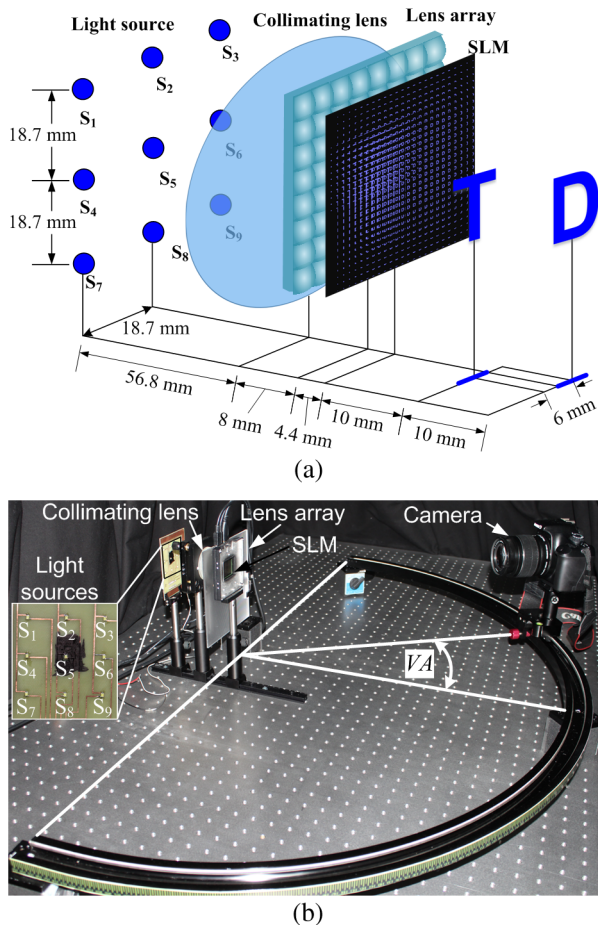| Light sources ($n \times n$)	VA_{max} (deg)	l_s (mm)
1×1	17.2	0
2×2	33.7	9.3
3×3	48.8	18.7
4×4	62.4	28
5×5	72.2	37.4

(a)

Fig. 3 Configuration of the proposed system (a) with objects and (b) experimental setup.

Figure 3 shows a configuration of the proposed system and an experimental setup. Nine LEDs, instead of a light-source array (3×3), were used in the experiment, and they were soldered onto a printed circuit board [Fig. 3(b)]. The distance between two LEDs, given by Eq. (3), was 18.7 mm.

In the first experiment, the PLSs in two cases were checked whereby only the center light source S_5 and then all nine light sources were on. The pictures of the PLSs were taken when the diffuser was at the PLS plane and the center light source S_5 was on [Fig. 4(a)], and the results were the same as those for the conventional PLS display. In
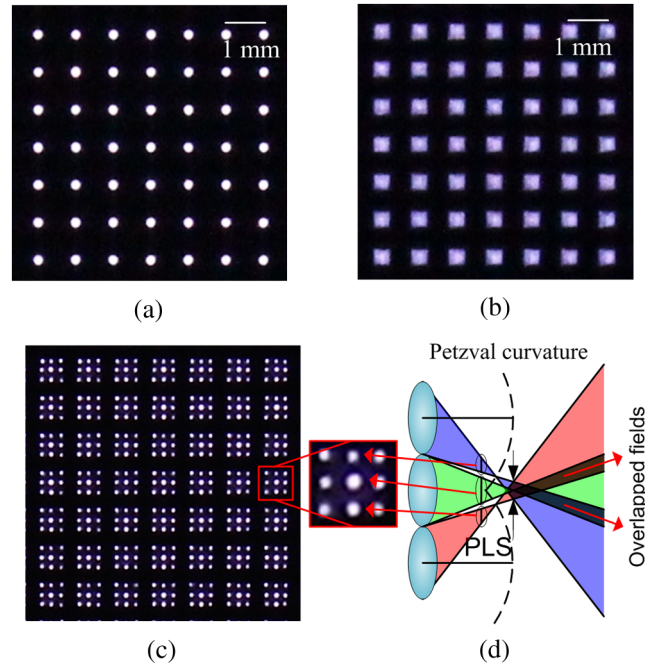
Fig. 4 Result of PLSs: (a) with one light source, (b) with nine light sources and a diffuser in the PLS plane, (c) with a diffuser 3 mm from the lens array, and (d) the overlapping fields.

the second experiment, the nine light sources were on and the diffuser was in the PLS plane [Fig. 4(b)]. The shape of the PLS was rectangular because the nine LEDs were placed in a rectangular manner on the printed circuit board. The size of the PLS with the nine light sources was larger than with the one central light source due to aberration of the elemental lens, and this is explained by Petzval curvature.[17,18] In Fig. 4(d), the dashed lines show the Petzval curvatures of the up and down elemental lenses; thus, the light fields from the up and down sources overlap when they are far from the PLS plane, and they are separated when they are between the lens array and the PLS plane [Fig. 4(c)]. From the experimental result, when the diffuser between the lens array and the PLS plane is located 3 mm from the lens array, the light fields separate and the sizes of the fields differ because of the Petzval curvature. Thus, the size of the center field is larger than the up and down fields in Fig. 4(c). According to Figs. 4(a) and 4(b), the distances between the two PLSs were the same, so we can conclude that the resolutions of the conventional and proposed method are same because Park et al.[6] determined that the resolution is limited by the number of PLSs.

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. That is, 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
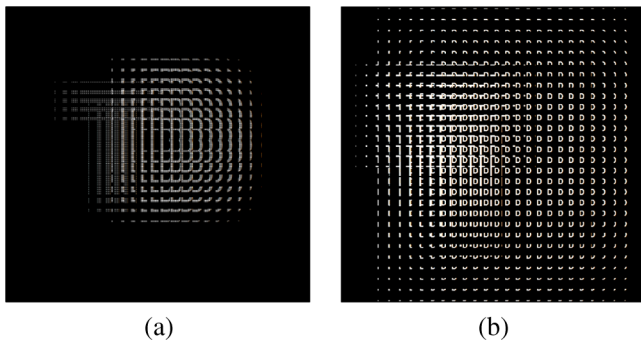
Fig. 5 EIs for (a) a conventional PLS display and (b) the proposed method.

Fig. 6 Experimental results of the proposed method at different VAs. (Video 1, mp4, 667 KB [URL: http://dx.doi.org/10.1117/1.OE.56.5 .053113.1]).
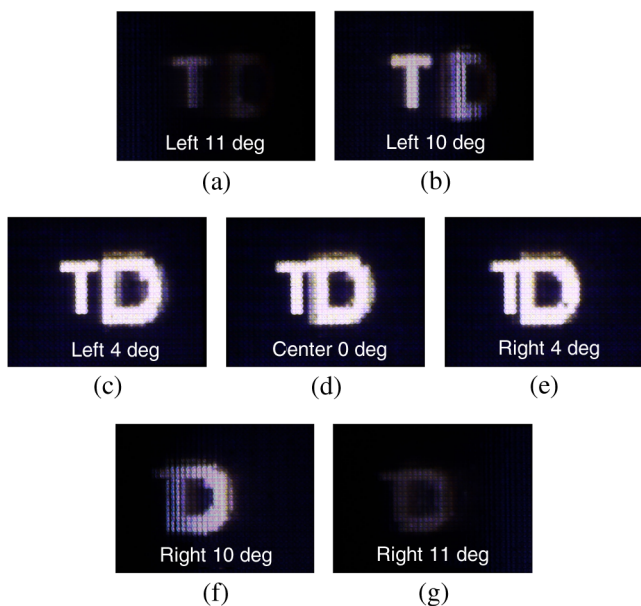
Fig. 7 Experimental results with one light source.

duplicated "T" and "D" are evident when the VAs are at left 10 deg and right 10 deg, respectively, because of the over-lapped 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 multiplex-ing 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 $n \times n$, 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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