Multi-projector-type immersive light field display

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Received March 31, 2014; accepted April 4, 2014; posted online May 28, 2014

A light field three-dimensional (3D) display with multi-projectors and a concave screen is proposed. The system sets the viewing area at the center of the concave screen, making viewers enter the center of the system to watch 3D scene around them. The surrounded 3D scene provides viewers a feast of enhanced immersive experience. The light field principle, rendering algorithm, selection of viewing area and experimental results are discussed in the letter, showing the potential of being an all-around-type immersive 3D display by employing more projectors.

OCIS codes: 110.0110, 120.2040.

doi: 10.3788/COL201412.060009.

1. Introduction

Light field displays have attracted numerous attentions since it was proposed, as it can provide real three-dimensional (3D) images with smooth parallax. Parts of light field displays intend to set up a square viewing region for 3D scenes just like conventional two-dimensional (2D) displays[1−3]. Others try to build a certain central space for viewers to watch around[4−6]. An immersive 3D display that reconstructs 3D scene for things surrounding viewers will definitely increase the watching experience, as humans are living in 3D space seeing 3D scene all around everyday. Immersive displays with scene surrounded are widely used in conventional 2D displays to build more natural and vivid perception for viewers[7,8]. However, few 3D displays successfully reconstruct surrounded scene for immersive experience.

In previous work, we have proposed several displays based on light field reconstruction principle[5,6,8]. The light field reconstruction algorithm has been analyzed[7]. Performance of the diffuser screen and arrangement of the projectors have been discussed[8]. Conventional multi-projector-type light field display with viewing position outside the system, suffers the problem that the projection angle of the projectors limits the viewing size of the system, leading to truncation to the whole reconstructed image. To widen the viewing size, a greater projection angle is necessary, which will increase the difficulty of manufacturing.

In this letter, a novel immersive 3D display system using light field reconstruction principle is proposed. A concave screen is employed to set up a space in the center of the system for viewers to enter. Projectors are configured around the screen with projecting images to the center of the screen. The viewing area is designed inside the screen and with its viewing field depending on the configuration of projectors. Inside the designed viewing area, all the employed projectors can be seen at the same time without moving the viewing position. The jointed observing created inside the concave screen makes it possible to create 3D scene around the viewers, demonstrating an immersive experience with 3D perception.

2. System Overview

A. System Structure

The system, illustrated in Fig. 1, consists of multiple projectors and an arc diffuser screen. The projectors are distributed along a circle that is homocentric with the screen, so that panoramic view can be attained by

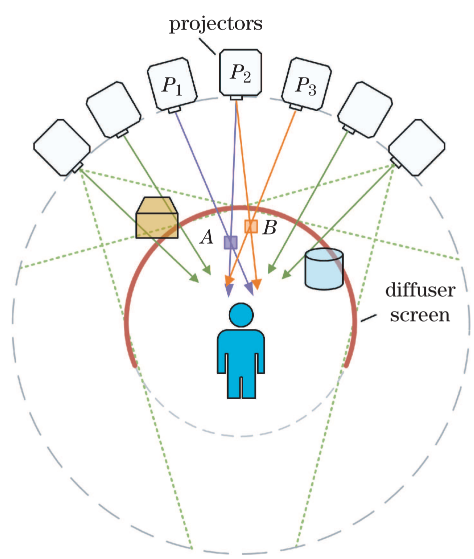

Fig. 1. Illustration of system structure.

adding more projectors to complete the circle. The common viewing area is inside the screen. People stand near the central area to enjoy the 3D images reconstructed by the projectors and the screen, achieving an immersive feeling.

The light field reconstruction algorithm has been introduced in many other papers[1,5,7,9]. In the certain system with two different spatial points A and B for instance, shown as Fig. 1, they are projected by different projectors to provide different depth perception. Projector P_1 and P_2 offer the binocular images of point A while P_2 and P_3 offer that of point B. To a single projector, its light rays projected pointing to different directions are used to reconstruct objective light emitted for different directions for observation, thus reconstructing the light field for some certain position and direction.

The system offers only horizontal parallax. Therefore, a special diffuser screen is employed with light rays diffused a small angle in horizontal direction while a large angle in vertical direction. Viewers will see the aperture of the projector diffused to a vertical stripe image though the screen. When the apertures of the projectors are dense enough and the horizontal diffusing angle of the screen is appropriate, the stripe images will join together to form a complete image. The image changes at different viewing position, leading to binocular parallax.

B. Rendering Algorithm

As what in above subsection discussed, the diffuser screen diffuses different angle in horizontal and vertical directions, which means that different algorithms shall be applied in the two directions. For the horizontal diffusing angle is used to widen the pupils to join the stripes, it is equivalent to employing wider pupils and a diffuser without horizontal diffusing angle. Detail about the diffuser screen has been discussed in previous work[8]. The algorithm then can be discussed in two directions. Here, the rendering relationship for this system is shown in Fig. 2. From the relationship, the algorithm for single projector can be described by

$$\begin{cases} x' = \dfrac{xR_{\mathrm{P}}}{z+R_{\mathrm{P}}} \\ y' = \dfrac{R_{\mathrm{P}}}{R'+R_{\mathrm{P}}}\Big[\dfrac{(y-h_{\mathrm{V}})(R'_{\mathrm{V}}-R')}{R'_{\mathrm{V}}-z}+h_{\mathrm{V}}-h_{\mathrm{P}}\Big] \\ \qquad +(R'+R_{\mathrm{P}})h_{\mathrm{P}} \\ z' = z \end{cases}, \quad (1)$$

For other projectors with interval angle θ, it is equivalent to rotate the spatial point with angle $-\theta$, thus the new point $\mathbf{A'} = \mathbf{AR}(\theta)$, where $\mathbf{R}(\theta)$ is the inverse rotation matrix along z-axis. All the projectors are applied the same algorithm as the system is centrosymmetric. Detail about the similar deduction is shown in reference Ref. [7].

3. Display Area

For an immersive system, it is important that when viewers enter the viewing area, they can see scene around them as much as possible. As the projection angle of projectors is limited, meaning that the viewing area are limited. The screen shall be set around the viewing area to ensure all the scene provided is seen inside the screen. The red circle in Fig. 3 shows the common imaging area of the multi-projector system. The common area that light emitted from all the projectors can reach is a circle that is tangent to the boundaries of the projection, with its radius:

$$R = D\sin\omega. \quad (2)$$

Where D is the distance from the exit pupil of the projector to the center of the system, ω is the half of projection angle.

It is significant that viewing area is truncated if viewers are watching images outside the common display area. As Fig. 3 shows, for certain viewing distance L, which calculated from the observing position to the center of the system, the viewing angle θ is determined by

$$\theta = 2\sin^{-1}\frac{D\sin\omega}{L}. \quad (3)$$

The two edge-projectors viewers can see, called P_L and P_R for instance, are determined by the viewing distance L, shown as the blue and the green characters in Fig. 3. Generally, if a convex screen is set, or a concave screen is set but the system size is not large enough for viewers to get close enough, the viewing position is out of the common area. So that viewers can only see parts of all the projectors. However, if the system size is large enough for viewers to enter the public area, meaning

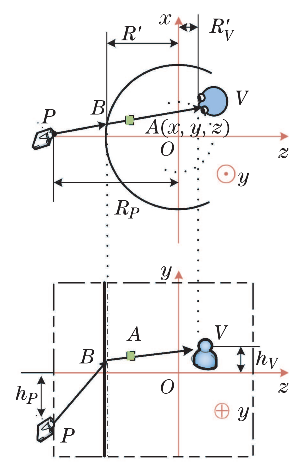

Fig. 2. Rendering Algorithm for the system.

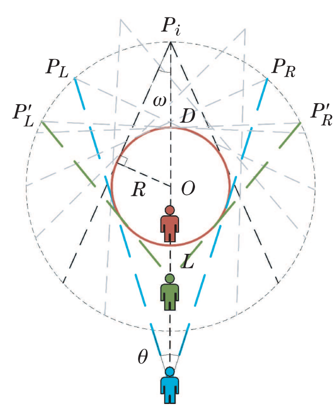

Fig. 3. Illustration of the public viewing area.

that $L < D\sin\omega$, all the projectors will be seen at the same time, shown as the red character in Fig. 3. The position $L = R = D\sin\omega$ yielding $\theta = 180°$, which is at the edge of the common viewing area, is the critical position. In this case, viewers can see an image with large view angle, even panoramic view field if the projectors' configuration is able to complete a circle. By setting the screen just outside the public viewing area, viewers are limited inside the viewing area to ensure the largest viewing angle.

4. Experimental Results

A. Prototype

A prototype of the system is set up using 90 projectors. Specifications of the prototype are shown in Table 1.

A snapshot of the prototype is shown in Fig. 4. The white grid displayed in Fig. 4 is approximate 7.0×4.5 (cm), and the blue lines are at the middle of each projector's picture. Viewers can see a complete image with size at least 0.8×0.4 (m).

With 90 projectors applied, the prototype can offer an image with 90° viewing angle. When viewers are standing near the center of the system, distance from screen to eyes is 40 cm. A concave screen will make viewers feel themselves surrounded with 3D scene, leading to a strong immersive experience.

B. Public Viewing Area

As Fig. 5 shows, 8 edge positions are chosen to show the public viewing area of the prototype, where A, B, C and D shows positions inside the area, while A', B', C', and D' shows positions outside. 60 projectors in the center are chosen and project 3 different colors to distinguish each other, where blue is in the leftmost and the red is in the rightmost.

Table 1. Specifications of the Prototype

Number of Projectors	90
Resolution of Single Projector (H×V)	800×600
Projection angle (H×V)	≈13°×11°
Angle of Adjacent Projectors	1°
Distance from Projectors to the Center of System	1.6 m
Radius of Diffuser Screen	0.4 m
Diffusing Angle (H×V)	1°×60°

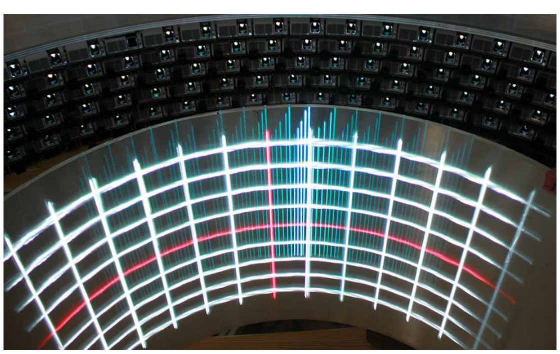

Fig. 4. A picture of prototype.

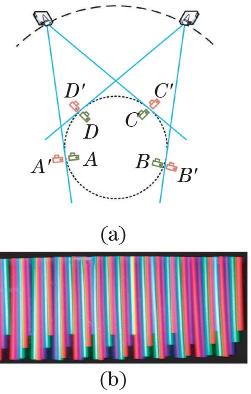

Fig. 5. Experimental scheme for showing public viewing area. (a) shows positions chosen for the experiment, and (b) distinguishes different projectors by different colors.

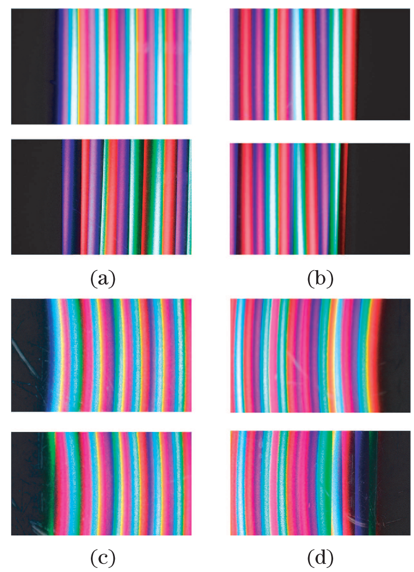

Fig. 6. Illustration of viewing positions inside or outside the public viewing area. In each sub-figure, the picture upper is taken inside the public viewing area while the lower is taken outside.

Figure 6 shows the trend that edge projectors can be seen at the positions inside, while some of them start to disappeared at the positions outside. It shows that viewers can see all the projectors inside the public viewing area in any direction.

C. Depth Range

An experiment employing a 3D model of a small ball and the SSIM algorithm[10] is proposed to help figure out the depth range that the prototype reconstructs. The ball is put at different distances from the screen position then captured by a camera set at the center of the system. The images captured then is compared with the original image of the model (Fig. 7(a)) and the comparison is presented by SSIM index. We can see that the images that the ball is at the screen position (Fig. 7(b)) is more similar to the original one than which further from the camera (Fig. 7(c))or nearer to the camera (Fig. 7(d)). Finally a graph indicates the relationship of the distance of the ball from the screen position and the SSIM index is shown in Fig. 8.

In Fig. 8, the x-axis indicates the distance from the screen position, where the positive direction directs to the camera, or the viewing position. The y-axis is the SSIM index, which the higher value indicates a more similar image pair. We can see the model put near the screen positions have the higher similarity, while the similarity falls when the model is away from the screen. What's more, the similarity falls even faster when the model is getting close to the viewing position than getting away from it.

Six people are invited to point out the tolerance of the depth range. The experiment shows an average far distance and near distance of 120 and 70 mm respectively. It indicates that a threshold SSIM index=0.5 can be drew in Fig. 8, showing a total depth range approximately 180 to 200 mm.

D. 3D Scene

Figure 9 shows 3 different viewing positions of the same model. From the occlusion shown in the three pictures we can see that the prototype can display a large viewing angle.

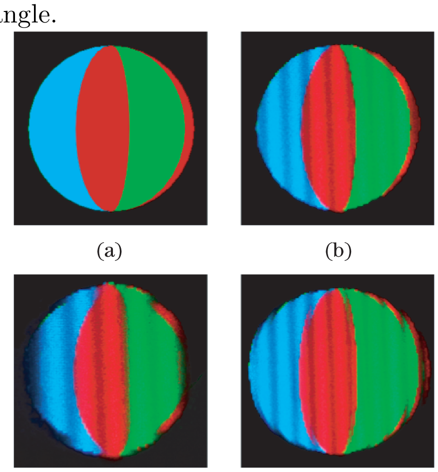

Fig. 7. Illustration of images of the (a) the original model, and the reconstructed model putting (b) at the screen position, (c) further from the camera, and (d) nearer to the camera.

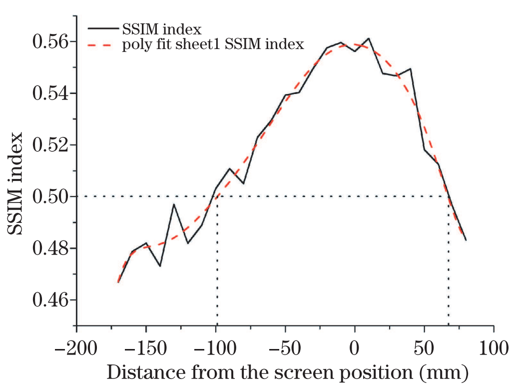

Fig. 8. SSIM index for the original image and images of the same object from different distances.

Fig. 9. Three different viewing positions of the same 3D model.

The experimental result shows that the prototype with 90 projectors can reconstruct 3D images with large viewing field and viewing angle. All the projectors can be seen at the same time in the public viewing area, providing a feast of immersive experience. Motion parallax is achieve and occlusion relationship is accurate.

5. Conclusion

Compared to the previous work, here we achieve 3D immersive visual experience with employing higher-quality projectors and a concave designed diffuser screen. 90 projectors are employed with adjacent angle 1° to offer a viewing field of 90°. The concave diffuser screen with radius 0.4 m makes common viewing area set inside the screen, which acts key role on enabling viewers perceiving whole reconstructed 3D scene around them at same time. The prototype successfully reconstructed 3D scene with large viewing angle and motion parallax, with a depth range about 180 to 200 mm. Stronger immersive experience will be achieved by adding more projectors to widen the viewing angle and perfect the display quality.

6. Acknowledgement

This work was supported by the National High Technology Research and Development Program of China (Nos. 2012AA011902 and 2012AA03A302), the National Natural Science Foundation of China (No. 61177015), the National Basic Research Program of China (973 Program) (No. 2013CB328802), and the Fundamental Research Funds for the Central Universities of China (No. 2012XZZX013). Great thanks to the State Key Lab of Modern Optical Instrumentation, Zhejiang University, for providing the necessary support.

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