Research Summary on Light Field Display Technology Based on Projection

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Abstract. In recent years, three-dimensional display technology has developed rapidly, among which light field display technology is a type of technology with broad application prospects that can realize naked-eye stereo display. With the enhancement of digital image processing capabilities and the development of projection technology, projection-based light field display technology has also made great progress. This article analyzes the principle and development of light field display technology based on high-speed projection and projection arrays, briefly introduces the relevant experimental results of the research team at home and abroad, and finally discusses the application prospects of different technical directions.

1. Introduction

Vision is the most important way for humans to perceive the external environment. The visual information received by human eyes accounts for more than 80% of all external information received by humans. In the development of human society, we have been pursuing accurate records and descriptions of the real world. But for a long time, the development of flat display devices has not got rid of the limitation of two-dimensional display. The three-dimensional scene displayed on screen is only a two-dimensional image of a three-dimensional scene at an angle, instead of a true three-dimensional scene with a full view. And even the polarization stereo projection equipment commonly used in theaters only reconstructs the three-dimensional scene at a certain viewing angle, and cannot achieve the full-view reproduction of the three-dimensional scene, which also needs to wear specific polarization glasses. Although the popular head-mounted virtual reality display devices can present three-dimensional scenes with different perspectives according to the position and posture of the person, they are also limited by the weight and performance of the device, with insufficient refresh rate, and discomfort such as dizziness when worn for a long time. However, the three-dimensional display system based on light field reconstruction appeared in recent years can solve this problem well, which can realize:

- The viewer does not need to wear additional equipment such as glasses or helmets to observe the three-dimensional scene, and the experience is comfortable, without fatigue;
- A three-dimensional scene image with a continuous and smooth perspective can be generated, and the viewer can observe the three-dimensional scene at a perspective in different directions and positions relative to the scene;
There is no limit to the number of viewers. As long as the viewing angle of the system is within the range of the system's field of view, the viewer can see the three-dimensional scene images in different perspectives without distinction.

This article is a brief introduction and summary of the related experiments of light field display technology based on projection arrays at home and abroad in recent years to help researchers understand the relevant research progress in this field.

2. Background and significance of 3D display technology

People have been exploring new display technologies to obtain a better viewing experience. In recent years, many true 3D display technologies have developed rapidly, such as volumetric 3D display technology, raster 3D display technology, integrated imaging technology, and holographic 3D display technology, all committed to reproducing the spatial light field. The rotating structure of the volumetric 3D display technology limits its ability to display large-scale 3D scenes; the raster 3D display technology and integrated imaging technology rely on flat displays to reconstruct the light field, although the flat display technology has also been in fast development recently, but the improvement of resolution is still slow, which limits its spatial bandwidth. That is, not enough light field information can be reconstructed, and this causes the mutual restriction of field of view, visual resolution, and display depth, which can be overcome by using projection arrays. This kind of technology can reconstruct more light field information, and the display effect naturally become better. For 360° full viewing angle display, other three-dimensional technologies are even more powerless. Only the projection array can get rid of the limitations of flat-panel displays to construct a circular field of view. The 3D display technology based on the projection array can break the limitations of traditional 2D display or single-view 3D display, provide greater spatial bandwidth, realize full parallax dynamic display of true 3D scenes, and give people a more realistic and comfortable viewing experience. It has broad application prospects, such as:

- Applied to military training. Through the light field display technology based on the projection array, the commanders and fighters can be immersed into the scene, display the combat opponents, simulate the combat environment, exercise and improve their ability to respond to various situations that may be encountered in the real battlefield and combat mission capabilities;
- Applied to medical diagnosis to construct and display a three-dimensional model of the affected area, which helps medical staff to diagnose the condition intuitively and accurately, find the lesion, and treat the wounded and sick;
- Applied to education and teaching. It can simulate and display various three-dimensional scenes, such as vehicle gearbox, aircraft engine, human bone structure, etc. Learners can intuitively understand the internal structure and mechanism of complex devices and improve learning efficiency;
- Applied to rapid manufacturing design. Real-time construction and display of three-dimensional models are carried out while designing, without making samples, and quickly making modifications;
- Applied to remote meetings. It can project three-dimensional portraits of the same size as the actual participants on the remote end, which is convenient for multi-party discussions and makes meetings more immersive.

There are already a variety of 3D display solutions, including color separation 3D display, polarized 3D display, shutter 3D display, head-mounted 3D display, gratings 3D display, integrated imaging 3D display, volume 3D display and holographic 3D display technology. But in order to achieve the dynamic display effect of large viewing angle, high resolution and large depth of field for multiple viewers, with a comprehensive comparison, the projection type light field 3D display technology is the best solution. Nowadays, with the development of computer graphics and computing power greatly improved, the realization of the light field display based on the projection array has full feasibility.
3. Development of 3D display technology based on projection

3.1. Light field display theory
When the human eye observes an object or a three-dimensional scene, the retina actually receives light of different wavelengths and intensities from the surface of the object in various directions. The distribution of light in space is called light field[1], which is to achieve naked eye three-dimensional display. To reconstruct the light field in space, let people see the same or similar light field as the actual three-dimensional scene, so that people can truly perceive the three-dimensional light field of the three-dimensional scene in space. In 1991, Adelson et al. proposed a plenoptic function to describe the spatial light field[2], which used the position of the light source, the azimuth of the light, the wavelength of the light wave, and the recording time of the light field to characterize the light in 7 dimensions. In 1996, Levoy et al. proposed to use a four-dimensional function to record the light field with negligible light wavelength and time[3], which is called 4D light field. Generally, the coordinates of two parallel planes through which the light passes are used as parameters to characterize its direction, as shown in figure 1. This is actually the loss of part of the light information parallel to the reference plane, but this part of the light information does not enter the human eye, so it can be selectively ignored. We only need to find a way to reconstruct the light field of the partial view angle of the 3D scene. In this way, the human eye could perceive the three-dimensional effect in the field of view.

![Figure 1. Principles of 7D plenoptic function and 4D light field function.](image)

Regarding light field display, at present, many laboratories at home and abroad have carried out design attempts of different experimental schemes, mainly including light field display based on high-speed projection and light field display based on projection array.

3.2. Light field display based on high-speed projection
The realization of a light field display system based on high-speed projection generally requires a high-speed projector and a rotating directional scattering screen. Projectors usually use LCoS(Liquid Crystal on Silicon) or DMD (Digital Micro-mirror Device) to achieve a high refresh rate. The directional scattering screen is an anisotropic light field control device that makes the light passing through it has different scattering angles in horizontal and vertical directions, and its high-speed rotation can make a fixed high-speed projector simulate a virtual projection array surrounding the scattering screen. The principle is shown in figure 2:
The Jones team in the United States proposed a light field display technology that can simultaneously present interactive 3D images to multiple viewers around 360° at the SIGGRAPH conference in New York in 2007[4]. The display system includes a high-speed video projector, a rotating mirror covered by a holographic scattering film, and an FPGA circuit for decoding specially rendered DVI video signals. It uses a standard programmable graphics card to render more than 5,000 interactive images per second. This system projected at a speed of 20 frames per second, with a separation of 1.25 degrees, and 288 field of view angles, as shown in figure 3:

![Figure 3. The 360°light field display system structure and display effect of Jones team.](image)

The Jones team also designed a quasi-real-time remote 3D telephone system based on this system[5] to track the eye position of the participants, obtained the correct vertical viewing angle, and further achieved two-way eye contact, which can reconstruct the effects of gaze, attention and eye contact that traditional teleconferences lacks. The system is limited by the data bandwidth of high-speed projectors, which can only realize the construction of grayscale scenes, and cannot realize the interactive experience of touching the virtual three-dimensional scene.

![Figure 4. Remote eye contact 3D conference system.](image)
Microsoft’s Alex Butler research team designed a desktop 360° interactive three-dimensional scene imaging system called Vermeer[6], as shown in figure 5, which combines a high-speed projector with a parabolic mirror to reconstruct light field near the focal point of the parabola. It is constructed to realize the display interaction without barriers to the three-dimensional scene, but the structure is huge and the image is small, with the display quality not good enough.

Figure 5. Vermeer’s structure and interactive display effect.

In addition, domestically, the Liu Xu research team of Zhejiang University has also designed a floating light field 3D display system that uses a high-speed projector and a flat light field scanning screen to create a real 3D scene light field in the air above the rotating screen. The face detection system built a vertical parallax [7], and multiple viewers can watch images from different perspectives at the same time. However, this method is only suitable for viewing from a bird's-eye view due to the limitation of the optical characteristics of the screen.

Figure 6. The principle (a) and effect (b) of the projection display of Zhejiang University.

3.3. Light field display based on projection array
In the use of projection arrays for three-dimensional display, many teams have also tried and achieved impressive results.
In 2006, the Balogh team in France used 64 projectors, a plane scattering screen, and two mirrors to build a three-dimensional display system named HoloVizio[8]. The projector resolution is 1024×768, and the scattering screen is diagonal. The length is 1.8m, and the horizontal angular resolution of the system is 0.8°. It is driven by 16 PC arrays and has a field of view of 50°. The principle is shown in figure 7. And through 27 CCD cameras to take real-time photo of the three-dimensional scene, it achieved rapid data update from the acquisition end to the display end [9], and also added a gesture recognition function, which can perform simple gesture operations on the displayed model, with good interaction effect[10].

![Figure 7. HoloVizio’s multi-view display effect.](image)

In 2013, Liu Xu from Zhejiang University and others built a multi-projection light field display system based on a circular projection array and a cylindrical scattering film[11], as shown in Figure 8, using 360 circular projector arrays arranged in 5 height steps to reconstruct the 360° light field of the three-dimensional scene. It's horizontal angular resolution is 1°, and the use of 4 computers and multiple graphics cards to work together for image rendering can project a larger scene. In addition, Liu Xu's team also built a penetrating light field display system using a multi-projection semi-surround array [12], which allows viewers to obtain an immersive three-dimensional experience.

![Figure 8. The principle of circular projection array structure.](image)

In the same year, the Jones team at the University of Southern California also implemented a three-dimensional display system based on a projection array[13]. They used 72 projectors with a resolution of 480×320 and a curved directional scattering screen to construct a small-sized three-dimensional display system. As shown in figure 9, the display screen has a diagonal length of 15 inches, and the horizontal viewing angle range is 72°. Although the horizontally arranged projection array can only achieve multi-view display in the horizontal direction, the vertical movement parallax can be achieved by detecting the observer's eye position through Kinect. Despite the small range, the display effect is fine, which is worthy of reference.

![Figure 9. The principle of projection array display system.](image)
Figure 9. Jones team's three-dimensional display system structure and effects.

In 2016, the Shunsuke Yoshida research team in Japan developed a new desktop 3D display system[14], which can display virtual objects floating on the desktop without glasses, named fVisiOn. It used circular projectors arranged under the desktop and the cone-shaped scattering film as an anisotropic diffuser. A full-color 3D scene about 5cm high can be displayed, and multiple viewers can view the real-time 3D scene from any angle among 360° together without space constraints. The effect is shown in the figure 10.

Figure 10. Display effect of fVisiOn.

4. Future development trend
Judging from the development situation at home and abroad in recent years, there are many solutions for three-dimensional light field display by using projection arrays and high-speed projectors. Different research teams have made related attempts, and there are many experiments with better effects, such as the Jones team’s. Although the projection array only has a display range of 15 inches, the display accuracy and number of viewing angles are relatively high. On the whole, the miniaturization and refinement of projectors are developing rapidly, and the projection display effect is constantly improving, but there is no major breakthrough in the basic technical principles. Meanwhile, the development of high-speed projectors is relatively slow, and the mechanical structure of the rotating directional scattering screen matching high-speed projector limits the large-scale development of display scenes, and higher-speed projectors require more powerful graphics processing capabilities for simultaneous output. Thesall limit the development of 3D display technology based on high-speed projectors. The projection array can distribute the computing requirements to multiple computers and the display requirements to multiple projectors, so that more information can be displayed in a larger range at the same time, which is more advantageous than the display solution based on high-speed projectors. As the hardware performance of graphics processing has also been greatly improved, it is possible to output more and higher-resolution perspective projection images. Therefore, the three-dimensional light field display technology based on the projection array scheme will become the mainstream in the future.

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