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Simulation tools for light-field displays based on a micro-lens array

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Abstract

A group of tools has been developed to analyze the display performance of light-field displays based on a micro-lens array. The simulation tools are based on the principle of Snell's Law and the characteristic of human visual system, in which the optical aberrations of lens arrays and the focus of eyes have also been taken into account. Some important issues in light-field displays can be shown clearly before the fabrication, such as perspective views, view zones, crosstalk, color moire patterns, and also the depth information in light-field near-eye displays. Therefore, the developed tools can provide a useful approach to verify the improvement of new techniques and also give a reference of the final performance for a system set-up with optimal specification. To our best of knowledge, the developed tools is the first approach to analyze the performance of 3D displays considering the optical aberrations and the characteristic of human visual system.

Introduction

Three-dimensional (3D) displays are undergoing rapid progress in recent decades due to the advancement of computer science and optoelectronic. 3D display technique has already found various applications in different fields, such as medical visualization, computer aided design, and entertainment [1].

Most commercial autostereoscopic displays and 3D movies based on binocular parallax can only provide two or a few views of 3D scenes to let the views perceive depth cues [2]. When the users obtain 3D objects from these displays, their visual accommodation plane and convergence plane will mismatch with each other due to the display principle. That leads to visual confusion and fatigue, which have already been discussed by many psychophysical and usability studies [3]. Many approaches have been developed to realize 3D display with both parallax and focus cues, such as holographic displays, volumetric displays, and light field displays. Holographic displays [4-6] can reconstruct amplitude and phase of 3D objects, but, currently, the display system should be huge due to the usage of coherent light and the huge data. Volumetric displays [7-8] regenerate 3D scene with volume-filling data, in which objects can be made up by volumetric points. the Helix 3D display [9], the FELIX 3D display system [10], and the Perspecta 3D display system [11] have been developed based on this principle, and finds many applications. However, it is a common problem in volumetric displays that the image is semitransparent and an occluded part of the object could be observed.

Light field expresses the process in which viewers obtain light from the real world. It has received many attentions since the concept was first proposed. and reconstruct the light field of a 3D object in space. Light field displays can simulate the light from the real world and reconstruct the light field of a 3D object in space. When compared with other 3D displays, they can provide objects with full depth cues with less data. Selective-diffusing screen and mini-projectors have been employed to provide omnidirectional-view light-field displays [12-14]. 3D images reconstructed by the kind of method can be observed by multiple users around the system, and some prototypes can even provide a touchable vivid color 3D image floating in space. The 360-degree viewed light-field system is usually very huge, which may limit its commercial application. A layered 3D display system is a type of light field displays which is made up of multiple planar display panels [15]. Huge computation cost has been used to make full use of the pixels on the layers, and each light ray cannot be reconstructed by the pixel individually. A micro-lens array is also one kind of devices to produce light field in space, which is also called as integral imaging methods [16-18], which have been paid a lot of attention in research and industry fields. This kind of displays can provide a light field based on a planar panel device, and the light ray can be controlled and rendered separately.

Offering a type of solution to private wearable computing and displays, near-eye displays have also provided great application potential, especially virtual reality and augmented reality industry are currently prosperous [19]. Commercial near-eye displays can also realize 3D sense with binocular parallax, but again it suffers from the problem of the conflict between accommodation and convergence. Multiple focal planes [20], holographic methods [21], and etc. have been employed to alleviate this problem. Among these methods, light-field near-eye displays [22], such as integral imaging based displays, have been treated as one of the most potential solutions [23]. In order to generate light field into human eyes, a micro-lens array is usually used in light-field near-eye displays.

As mentioned above, light-field displays based on a micro-lens array are a hot point not only in 3D displays with naked eyes, but also in near-eye displays. However, display performance is usually analyzed based on the set-up of ideal systems, and the final results often vary a lot from the theoretical analysis. Many factors will all contribute to the final performance significantly, such as the optical aberrations of lens arrays, the organization of sub-pixels on the display panels, the 3D rendering method (display patterns on the panel), the eye position, and the characteristic of human visual system. Therefore, a tool to simulate the above items synthetically is necessary during the design process to show results close to actual performance.

In this paper, a group of simulation tools has been developed to provide the display performance of light-field displays based on a micro-lens array. The optical aberrations and the characteristic of human visual system have been taken into account to analyze the performance of 3D displays considering Some important issues in light-field displays can be shown clearly during the design process, such as perspective views, view zones, crosstalk, color moire patterns, and also the depth cues in light-field near-eye displays.

Methods

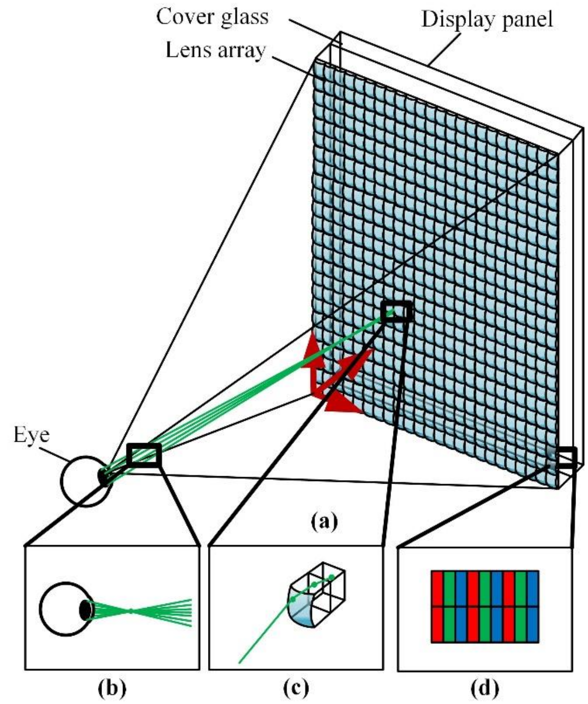

Figure.1 Diagram of the developed simulation method to analyze the display performance of light-field displays based on a micro-lens array. (a) System set-up in the simulation tools. (b) The organization of subpixel on display panel. (c) Ray tracing according to Snell's Law. (d) Calculation model of human vision system

A light-field display system based on a micro-lens array consists a planar displays panel, a micro-lens array, and sometimes a floating lens (an eyepiece in light-field near-eye displays). In this manuscript, the floating lens has not been taken into account in order to simply the simulation process. Adding the floating lens or more complex lens structure will not be a problem due to the same simulation process in the developed tools.

In order to simulate the process that the human views light-field displays, a 3D cartesian coordinate system is set with the plane OXY on the display panel and Z-axis on the same direction viewing the 3D images, as shown in Fig.1(a). The field of view can be separated into multiple equal parts from both horizontal and vertical directions, for instance, M×N parts. Thus, a 2D picture with M×N can be calculated for the simulation performance, and each part stands for a particular angle.

The eyes are set at any position facing the displays, and rays are sampled from the eye position to the particular system. The number of rays in one group can be one, but to simulate the focusing characteristic of human eyes, a simple model with a controllable aperture and focal point can also be employed to simulate human eyes. Multiple points can be randomly sampled within the aperture, and the focal point is set at the intersection between the field angle and the focal plane, which can represent the focal position of human eyes. The rays are traced from the points within the aperture to the intersection, which can simulate the aperture of the human pupil shown in Fig.1(b). As the rays can be expressed by the start point and its direction vector in the 3D cartesian coordinate system, the intersection point between each ray and the surface can be calculated. After refracted on the surface, the direction vector will be changed according to the Snell's Law [24].

One group of light rays can be traced from the position of human eyes to a particular field angle, and the rays are refracted by the lens array, the cover glass, and finally intersect with the particular pixel on the display panel. Thus, the value of this pixel is the value of this ray. The ray retracing process can be proceeded sequentially, as shown in Fig. 1(c). Therefore, it is no problem to insert other optical structures between the eyes and the display panel. The weighted mean of the pixel value for the particular ray group can be in the coordinating part in final display performance.

To analyze the color characteristics (such as moire patterns), R, G, B sub-channels should be calculated respectively, and the final simulation results can be obtained by blending these three channels, as shown in Fig. 1(d). In this case, the value of each ray mentioned above can be expressed as the value of the coordinating subpixel on the display panel after the ray-tracing program. Thus, human visual system and the optical aberrations have been taken into account in the developed simulation tools.

Results

Light-field displays set-up with naked eyes

Table 1. Parameters of light-field display set-up

Parameter	Specification
Lens Array	
Lens type	plano-convex
Shape	hexagon
Material	acrylic
Lens pitch	2.592mm
Focal length	7.292mm
Display Panel	
Pixel size	0.324mm
Resolution	1000pixel×1000pixel
Elemental image size	48 pixels
System	
Display mode	Real mode
Gap	8.2035mm

A light field display system analyzed by the developed methods are made of a micro-lens array and planar display panel. In order to reconstruct the light field of a 3D object, a 2D image should be displayed on the panel which can be calculated by a rendered method. Many types of light field displays have been developed to show 3D scenes, and a great number of rendering methods have been proposed. Experiments can be made based on a particular system to verify the proposed methods. The parameters of the experimental set-up are listed in Table 1, and the displayed image is rendered by the multiple ray cluster rendering method which shown in [25]. The shape of micolens is hexagonal, and the parameter is shown in Fig. 2(b). The pixel size on display panel is 0.324mm. The focal length of micro-lens is set as 7.292mm, and the display mode can be focal mode (when gap = 7.292mm) or real mode (when gap = 8.204mm). Each elemental image consists of 48 pixels, and the experimental rendering image is shown in Fig. 2(a), and Fig. 2(c) gives an enlarged part of the rendering image. The 3D cartesian coordinate system is set with the plane OXY on the center of the display panel, and the image is rendered based on a viewing distance of 2500mm. As described above, the simulation eye model can be located at any point in the space, and light rays were traced from the eye model to the display panel. 1000 × 1000 groups of rays are sampled, thus, the final simulation results can be shown as an image of 1000 pixels × 1000 pixels.

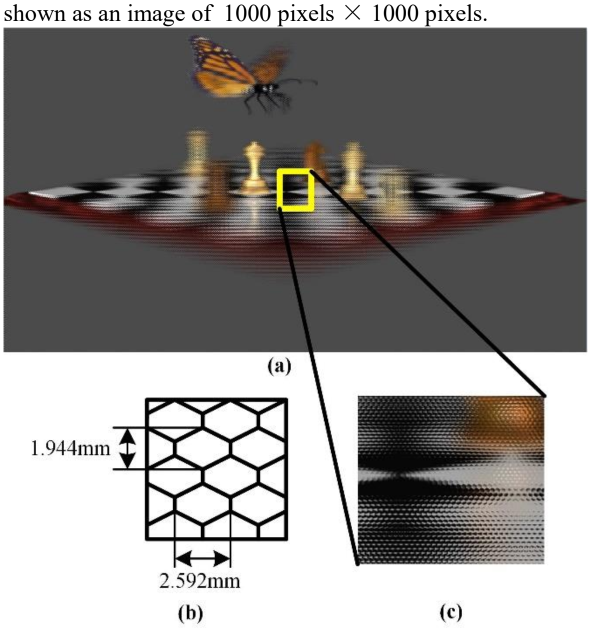

Figure.2 Diagram of the parameters in light-field displays with naked eyes. (a) Image on display panel which is obtained by light-field rendering methods, and the best view distance is 2500mm. (b) Parameters of the microlens array. (c) Enlarged image on the display panel.

Simulation results of crosstalk

3D displays provide a depth sense to a viewer by offering different views with parallax cues to different eye positions, but due to the system set-up, the image dedicated for one view may be leaked to the other view. This leakage of one image channel to the other in a 3D display system is known as crosstalk [26], which is often discussed in detail during the design process. Also, in designing the light-field display system based on a microlens array, the crosstalk is also an important factor when optimizing the system. Based on the experimental set-up, the coordinate of the position at the best view distance and the center facing the system is (0, 0, 2500). As the position of eye model moves around the best position, little crosstalk will be introduced, and this area with little crosstalk can be treated as view zone. When the eye model is located outside of the view zone, crosstalk can be found. Using the developed simulation tools, crosstalk can be analyzed before fabrication.

Display performance with different eye position have been shown in Fig. 3, which is obtained by the developed simulation tools. Fig. 3 shows the simulation images obtained with the eye position of (0, 200, 2500), (0, 400, 2500), and (0, 600, 2500) separately. From the simulation results, the first two eye positions are inside the view zone, and little crosstalk can be found in the simulation images. Moreover, images with parallax cues can be obtained in these two simulation images, and depth sense is provided when different views are given to different eyes. Clear crosstalk can be seen in the last simulation image; thus, the eye position is obviously outside the view zone. When compared with the view image of ground truth, the simulation results can also be used to measure the crosstalk based on the system with different paraments and different rendering methods.

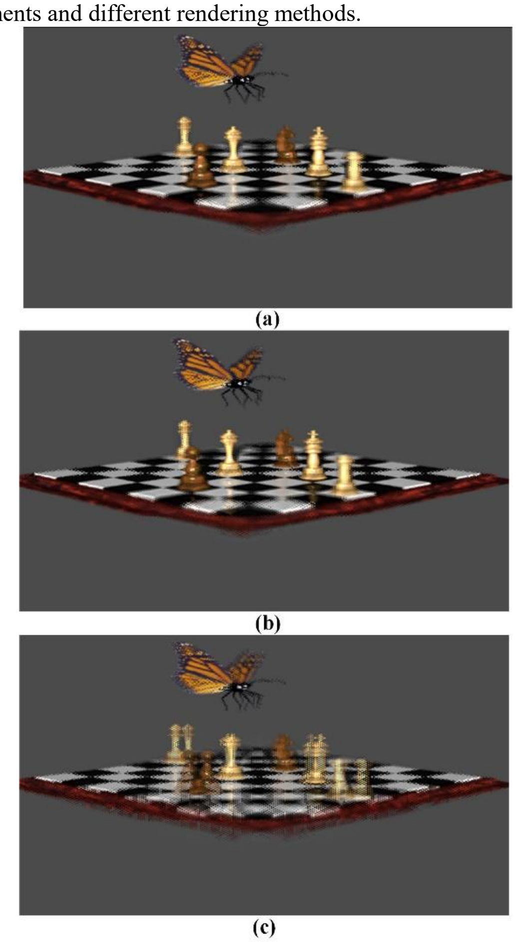

Figure.3 Display performance obtained by the developed simulation tools. (a) Simulation image obtained with the eye position of (0, 200, 2500), and the eye position is inside the view zone. (b) Simulation image obtained with the eye position of (0, 400, 2500), and the eye position is inside the view zone. (c) Simulation image obtained with the eye position of (0, 600, 2500). The eye position is outside the view zone, and crosstalk can be seen in the simulation image.

Simulation results of color moire patterns

The display devices typically provide color images by the combination of red, green, and blue subpixels, and each pixel consists of three rectangular subpixels. The color moiré pattern will occur, when these display devices are employed in the autostereoscopic method using a lenticular lens or the light field method using a lens array. That is because that the periodicity in geometry of subpixels interferes with the periodicity of the lens array [27]. The problem of the color moiré pattern will degrade the 3D display quality, and a lot of new structures have been developed to reduce this problem. The display performance analyzed by the developed simulation tools have been shown in Fig. 4 with color moire patterns. As mentioned in the method, R, G, B sub-channels should be calculated respectively, and the final simulation results can be obtained by blending these three channels.

Thus, the color moire patterns can be analyzed. The color moire pattern can be seen clearly in Fig. 4(a) when the system is focal mode (that is to say, the gap = 7.292mm). When the gap is set as the real mode, the simulation image can be shown in Fig. (b). The color moire pattern can be eliminated by changing the gap in light-field displays. Tilted elemental image array generation method and tilted lens array method have been proved to be useful in reducing color moire pattern [27-28]. The developed simulation tools can also verify the method by only changing the display pattern or tilt the lens array, which can also get a result during the optimization process before fabrication.

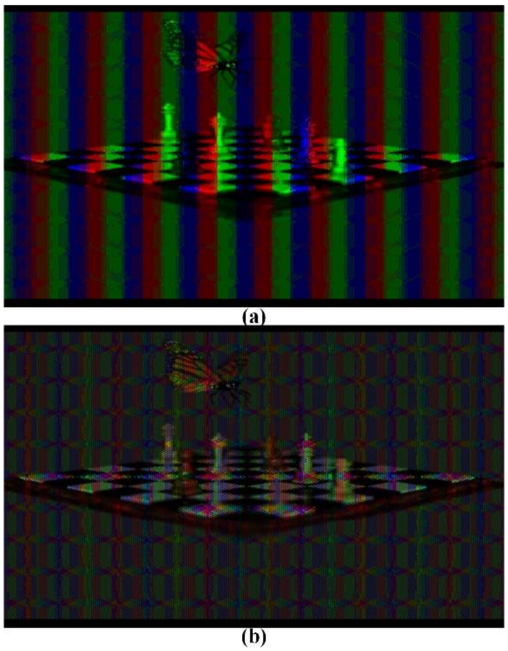

Figure.4 Display performance obtained by the developed simulation tools with color moire patterns. (a) Simulation image obtained with the system of focal mode (when gap = 7.292mm), and the color moire pattern can be seen clearly. (b) Simulation image obtained with the system of real mode (when gap = 8.204mm).

Light-field near-eye displays set-up

As mentioned in introduction section, light-filed near-eye displays based on a micro-lens arrays have been paid a lot of attentions currently. A micro-lens array and planar micro-display device are employed in the experimental set-up, similar to the method in [29]. The focal length and the pitch of lens array are 2.8mm and 1mm respectively. The pixel size of display panel is 15μm, and 300×400 pixels are employed in the system. Two objects are rendered at near field (350mm) and far field (1650mm) respectively, and the exit pupil is set at 50mm. The relationship of eye, display components, and virtual objects is also shown in Fig. 5(a). According to the principle of light-field displays, each pixel reconstructs one light ray in space. Based on ray-tracing rendering method, a 2D image providing 3D scene in Fig. 5(a) can be obtained in Fig. 5(b). In fact, an eyepiece, which is inserted between the eye model and the microlens array, only increases the intersection times of simulation rays [30]. The aperture of eye model can be set as 8mm, and 500 × 500 groups of rays are sampled; thus, the final simulation results can be shown as an image of 500 pixels × 500 pixels.

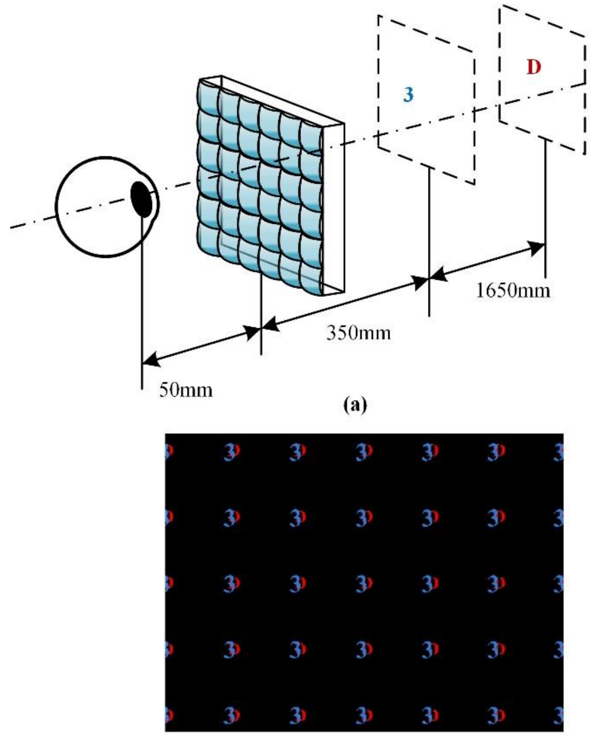

Figure.5 Diagram of light-field near-eye displays based on a micro-lens array, which can also be simulated by the developed tools. (a) Diagram of the parameters in the simulated system. (b) Image displayed on the panel.

Simulation results of visual accommodation in light-field near-eye displays

As a light-field near-eye display is one type of light field displays, some issues mentioned above can also be simulated in near-eye displays, such as crosstalk, moire patterns, and view zone (it is called eye box or can be treated as exit pupil in near-eye displays). The function of light-field near-eye displays is to solve the vergence-accommodation conflict exciting in traditional near-eye displays. Visual accommodation is an important issue in light-field near-eye displays. The simulation results shows that when the eye focuses on the near field, the farther virtual object (the letter 'D') become blur due to defocusing, vice versa.

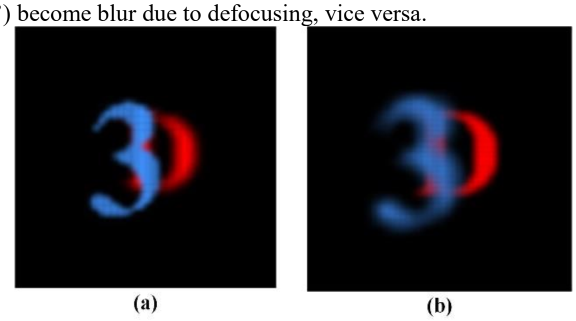

Figure.6 Simulation results by the developed tools. The human eye focuses on the distance at (a) 350 and (b) 2000 mm, respectively.

Conclusions

We have developed a group of simulation tools to provide the display performance of light-field displays based on a micro-lens array. Simulation results have shown that some important issues such as perspective views, view zones, crosstalk, color moire patterns, and visual accommodation, in light-field displays can be shown clearly before the fabrication, and the developed tools can provide a good reference during the design process. Future works include adding tolerance analysis, optimized process and depth resolution analysis into the developed tools to make them more comprehensive and completed in designing the light field displays.

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