A Horizontal Parallax Table-top Floating Image System with Freeform Optical Film Structure

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ABSTRACT

In this paper, a new structure of horizontal parallax light field 3D floating image display system was proposed. The structure consists of pico-projectors, Fresnel lens, micro-lens array and sub-lens array with freeform shape. By the functions of optical components, each light field of projectors could be controlled as a fan ray, which has high directivity in horizontal and wide scattered angle in vertical. Furthermore, according to the reverse light tracing and integral image display technique, horizontal parallax floating 3D could be demonstrated in the system. Simulated results show that the proposed 3D display structure has a good image quality and the crosstalk is also limited below 22.9%. Compared with other 3D technologies, this structure could have more benefits, including displaying real high resolution floating image, unnecessary of physical hardware on the image plane, scalability of large size system, without the noise from spinning component, and so on.

Keywords: Light Field, Floating Image, Integral Image, Freeform

1. INTRODUCTION

In recent years, there has been a dramatic proliferation of research concerned with the three-dimensional (3D) displays technologies. Nowadays, 3D display technologies have been wildly used for the electric products in the living environment due to the improved techniques, such as 3D movie, television, laptop, exhibition, electronic billboard and so on. Since the depth information could be detected by observers from 3D image system, the different distances of objects could be easily recognized and become more realistic, compared with traditionally planar display. Therefore, 3D display technologies could be believed to become the main stream in the next generation.

3D display technologies could be divided as two types, stereoscopic and auto-stereoscopic, by the necessary of 3D glasses or not [1]. Although stereoscopic display is a sophisticated technology and has good quality of 3D images, there still has some congenital defects could not be resolved, such as the inconvenient and uncomfortable feeling when observers wearing 3D glasses to watch stereoscopic image. Thus, the glasses-free 3D technique, auto-stereoscopic, would be the following research tendency in this area. Furthermore, the surrounding watching area and exhibiting floating image in the air are the pursing characteristics of 3D display system, so the tabletop type 3D system has been discussed recently and been more and more popular.

Unfortunately, there have been few studies to propose new tabletop 3D display structures and discuss the surrounding parallax floating image, because of the complexities of the light field controlling. According to whether the hardware of structure has dynamic component or not, the previous studies could be classified as two types. The first design contains dynamic element, such as rotating mirror, Fresnel lens, hologram or pattern medium, to reflect different directional frames in the corresponding viewing zone [2-4], as shown in Figure 1(a). This technology has advantage in simple structure, but it still has concussion, flicker and noise issues. And the other one is known as static type, which controlling

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light distribution by optical film design [5]. For example, in the Figure 1(b), the structure has taper type directional diffuser screen to splay light field in the vertical direction. This system is stable and quiet since it without dynamic component, but the blur image and weak expansibility problems should still need to be solved.

To overcome these shortcomings, a new design of tablet floating system to achieve displaying horizontal parallax 3D image is presented in this paper, which is static, quiet, expansible, and stable. Based on this proposed structure, the projected light field could be controlled by planar optical film with micro structures and the crosstalk value would be suppressed.

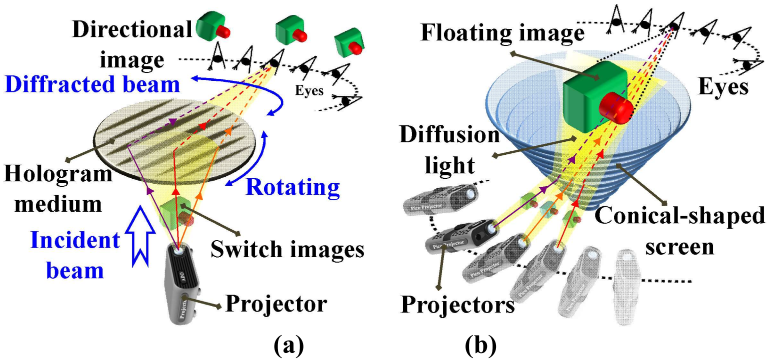

Figure 1. Scheme of glasses-free tabletop type 3D floating system with (a) dynamic and (b) static structures.

2. METHOD

The purpose of this paper is to build a new design of floating image system. To solve the weakness of mechanical rotated issues, the static type tablet-top 3D display technology was chosen. The first step in this paper is to consider and analyze the imaging principle. To simplify the complexity of light field system, just one dimensional, horizontal, parallax structure was chosen. The second step is to build the new proposed structure, which concluding five optical layers, pico-projectors, Fresnel lens, micro lens array and sub lens array, as shown in Figure 2(a). As the optimization of free-form optical films, the light field of projectors could be controlled as fan rays in the designed direction after passing through micro structures. Therefore, the table-top floating image system with static, quiet, expansible, and stable characteristics would be achieved.

2.1 Principle of 3D floating image in this design

In the design structure of this paper, one dimensional integral image system was used as the imaging principle. The optical film layer could be divided to several repeatable micro structure units, which receiving projected light from every projector. The total number of micro structure units could be assumed as image spatial resolution in this system. After passing through the optical films units, each light field of projectors would be controlled as a fan ray, which has widely scattered angle in vertical and highly directivity in horizontal direction. For convenience, the projectors were named by capital letters, and each fan ray was named by adding apostrophe in the end to correspond to the projectors, as shown in Figure 2(b). Furthermore, to define the angular parameters of fan rays, α and β are assumed as the angles of single fan ray covered range in longitude and latitude direction, which also indicated the splay angle and the collimated angle. Moreover, the angle between z axis and normal vector of fan ray is defined as tilt angle, γ, as shown in Figure 2(f).

After entering the working range of the display system, the image signals of opportune fan rays in the corresponding micro units could be received by eye pupils of observer, as shown in Figure 2(c). Thus, according to the integral imaging principle, the signals of fan rays could be accumulated as floating image on the retina.

Besides, when the observer moves the viewing position in the longitude direction, the fan rays of micro units would be changed to the different corresponding projectors, as shown in Figure 2(d). Since the signals of each projector in the same micro units are different, observer could see the floating object in the different angle of view.

Otherwise, the received fan rays of micro units are the same when observer moves the eyes in the acceptable latitude direction range, because light could be splayed in the vertical direction and image signals of each fan ray could be detected, as shown in Figure 2(e). In this case, the viewing angle of integral floating image on the retina is also the same since the unvaried relationship of light field incident direction and the micro component position. Therefore, this system has just one dimensional parallax effect.

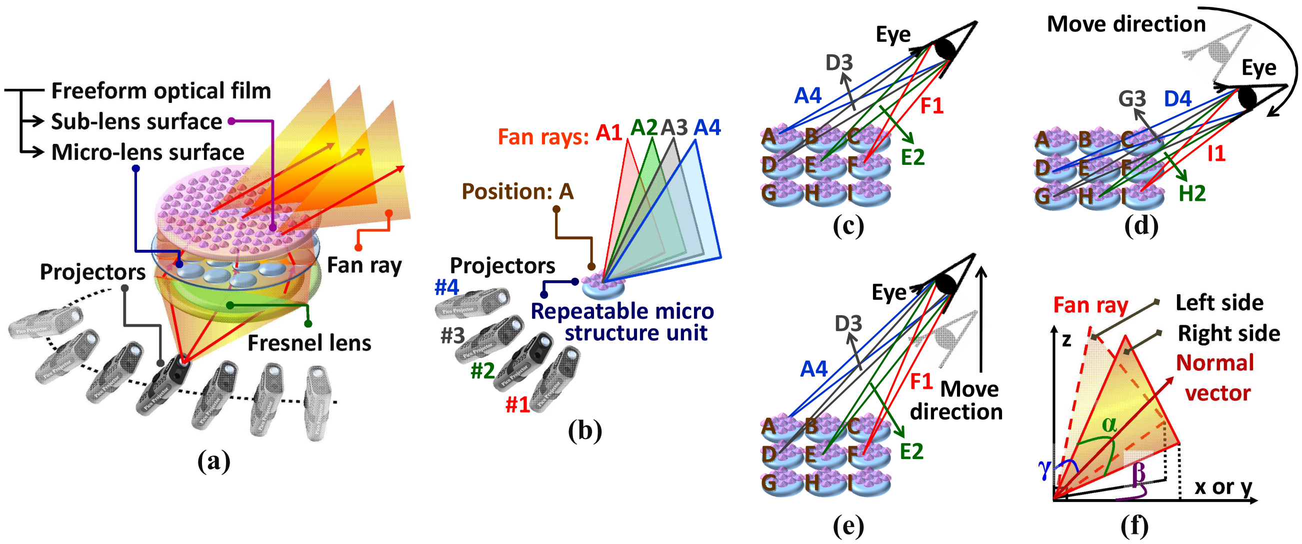

Figure 2. (a) Scheme of proposed floating image system; (b) The fan rays which corresponding projectors on a repeatable micro structure unit; The received fan rays by human eye (c) in a workable viewing area; (d) in the different longitude position; (e) in the different latitude position; (f) The angle definition of a fan ray.

2.2 Structure design of this new display system

The optical components of the new proposed structures could be simply regarded as five parts, such as pico-projectors, Fresnel lens, micro lens array and sub lens array. In this section, the design approach of each layer would be focused on, which including the arrangement of projectors, the free-form shape structure of micro optical film, and the fan ray design in the spatial and angular relationship.

To determine the number and arrangement of projectors was the first step of the design procedure. Considering the size of built equipment, the short focus length and small size pico-projectors were chosen in this system. Moreover, the collimated power of micro structure should also need to be figured out. According to the applied function,

$$\beta_{\max} = 2\times\tan^{-1}\left(\frac{d/2}{D}\right), \qquad (1)$$

the maximum covered angle of each fan ray in longitude direction, $\beta_{\max}$, could be easily calculated. In this function, the D and d parameters indicate the watching distance between observer and screen, and the gap between human's two pupils, which chosen as 50cm and 6.5cm by the setting and the means of statistics.By replacing these values into function, $\beta_{\max}$ could be calculated as 7.4°. Furthermore, the minimize amount of projectors, 48, could be evaluated by using 360 degree dividing $\beta_{\max}$.

Besides, the relationship between projectors' number with visual brightness and crosstalk should also be considered. When observer moves their eyes horizontally in the different viewing zones, the variety of brightness, black stripes, and the discontinuous signal in switching screens, ghost images, would be noticed, as shown in Figure 3(a). The main reason of this phenomenon is that the intensity profile of fan ray in longitude direction is much similar as Gaussian distribution rather than ideal flat-top distribution. Thus, when the viewing zones amount was increased, the brightness uniformity and the crosstalk value were improved, as shown in Figure 3(b). In this paper, 64 pico-projectors were used to display floating image in the surrounded viewing system, and the angle resolution could be defined as 5.625 degree in longitude direction, which was the covered range of each projector.

According to the distance of focus length, the projectors were placed under tabletop 60cm in this system. Moreover, based on the most comfortable viewing area, the tilt angle, γ, of fan rays were set as 45°. Figure 3(c) shows that the projectors were arranged as two circular permutations to display the image of surrounded viewing zones.To simplify the design of system, there are just nine projectors, which named by capital letters, from 'A' to 'I',in a half quadrant should be considered since the symmetry structure.

After emitting from projectors, light would be diverged to fill the full screen to display image. However, in the optical screen, the incident angles of light field varied with different positions, which inducing the difficulty of design and light controlling. Therefore, by inserting the Fresnel lens structurein the projectors'focal plane, the divergence angle of light would be changed as parallel rays before entering to the next optical component.

After passing trough Fresnel lens layer, the freeform optical film, which combining the micro-lens as bottom surface and sub-lens as top surface by solving the manufacturing para-position issue, was designed. And then the incident parallel light of projectors,which having different ejecting angle,would be changed the optical path and focused at the corresponding positions in the freeform film by the power of micro-lens array. As mention in the previous section, the micro lens could be assumed as structure unit and could be repeatable since the parallel incident light and the same conditions of each micro-lens. Thus, just one micro lens should be discussed and optimized in this structure. Moreover, by using lens maker's formula,

$$\frac{1}{f}=(n-1)\times\left[C_1-C_2+\frac{(n-1)\times w\times C_1\times C_2}{n}\right], \tag{2}$$

the characteristics of micro-lens could be figured out. In the function, n is the material index of micro-lens, and C1 and C2 symbol defines the curvatures of front and rear surfaces. Because micro-lens array was just the lower surface of freeform optical film, the C2 value had to be defined as 0 in this structure. And the f and w indicate the focal length and thickness of micro-lens.

Besides, in each observing position, the amount of micro-lens units and fan rays are the same, so the space limitation of floating image in this system could be defined as the smaller value of micro-lens number and projectors' resolution. To cooperate with the projected resolution, the micro-lenses amount would be chosen as 500 times 500 in this paper.

Moreover, to control the focus positions of each light field, there were two factors should be considered. The first one is the power of micro-lens surface, which means the ability of refracting light. And the other one is the thickness of the freeform optical film, which indicating the distance between micro-lens surface and sub-lens surface. For this structure, the larger area between micro-lens diameter and the farthest focus position in the sub-lens surface could be defined as the size of repeatable units.

Similarly, since the relationship between each light field focus position were influenced by the projectors' symmetry arrangement and the incident light of micro-lens surface was parallel, there were only nine freeform structures of 64 sub-lenses surface above single micro-lens unit should be considered, which named by lowercase letters, from 'a' to 'i', corresponding to the 'A' to 'I' projectors, as shown in Figure 3(d).

Furthermore, the freeform structure of sub-lens surface could be divided as two parts, the horizontal tangent direction and the vertical direction. For the horizontal part, the concave surface would be chosen as the shape of sub-lens, which has confocal characteristic with micro-lens' focal length, and the light field would be collimated, as shown in Figure 3(e). The curvature of rear surface, $C_1^{'}$, could be calculated by the function,

$$C_1^{'}=\frac{W_{ML}}{(n-1)\times f_{ML}\times W_{SL}}, \tag{3}$$

where the W_{ML} and W_{SL} are the diameters of micro-lens and sub-lens. And the f_{ML} symbol indicates the focal length of micro-lens.

Otherwise, since the light field distribution would be controlled as fan ray and scattered in the vertical direction, the prism structure was chosen as sub-lens' shape, as shown in Figure 3(f). According to the trigonometric function, the angle between emergent light and normal vector of prism's inclined plane, θ_o, could be evaluated by the applied function,

$$\theta_o=\sin^{-1}\left\{n\times\sin\left[\eta+\sin^{-1}\left(\frac{\sin\theta_i}{n}\right)\right]\right\}, \tag{4}$$

where the η is the inclined angle of prism, and the θ_i is the incident angle of sub-lens surface. Moreover, the light field focus positions of each projector and the incident angle of sub-lens surface, θ_i, could be calculated by ABCD matrix.

Therefore, the shape of sub-lens surface was designed as confocal concave lensshape in horizontal tangent direction and as prism structure in vertical direction. By the power of freeform optical film, each light field could be controlled like a fan ray, as the original purposed.

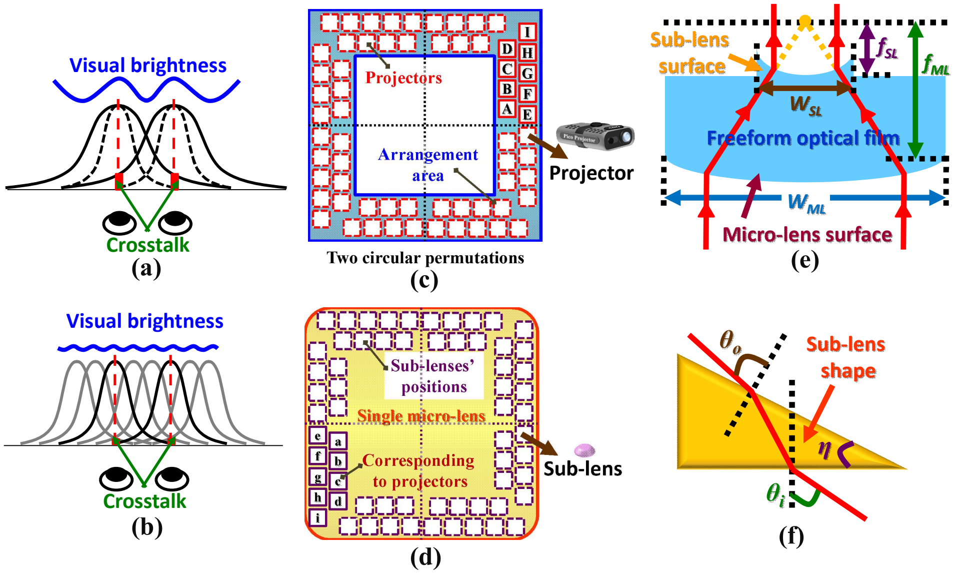

Figure 3. Visual brightness and crosstalk of (a) few and (b) many viewing zones; (c) The arrangement of projectors in this design; (d) The positions of sub-lenses above single micro-lens corresponding to the projectors; (e) The confocal structures of sub-lens and micro-lens in crossed plane; (f) The angle definitions of prism.

3. RESULTS

In the previous section, the structure of table-top floating image system would be decided. By the formulas of optical principle, the parameters and the characteristics of each component could be calculated and analyzed. Therefore, to confirm the optical properties, the proposed structure was built in the commercial optical software, LightTools, which widely used in the simulation of light distribution. In the simulation, the planar parallel light was chosen to represent the optical profile of projected light passing through the Fresnel lens. Moreover, since only single repeatable micro-lens unit should be verified, the absorber was built to filter the unnecessary light, which locating outside the micro-lens area.Besides, the micro-lens in the bottom plane of optical filmwas designed as convex surface, which curvature was chosen as 1.2mm^{-1}. For the sub-lens structure in the top plane of optical film, the confocal concave surface and prism shape were used in horizontal tangent and vertical direction, as shown in Figure 4(a) and Figure 4(b). Furthermore, the material of freeform optical film in simulation was set as BK7, which index is 1.5168.

According to the Monte Carlo simulated method in LightTools software, the light field distribution could be obtained, as shown in Figure 4(c), which is similar as original predicted. To achieve the purpose of smoothly changing floating images in different viewing zones, the covered range of single viewing zone in horizontal direction were chosen as twice, 11.25°, since the shape of fan ray could not be control as the ideal flat-top distribution. Table 1 shows the horizontal collimated range of each fan ray in sub-lens surface, and Figure 4(d) illuminates the angular distribution in the different latitudes of fan ray ‘a’, which having the scattered characteristic in vertical to improve the acceptable viewing area.

Based on the simulated results of this structure, there have some features need to be mentioned. Since the shape of micro-lens structure was chosen as spherical surface rather than parabolic type, the aberrations were appeared in the sub-lens surface, which influencing the light distribution of each fan ray. Besides, if the curvature of confocal concave surface in the sub-lens layer was too large, the total internal reflection would be appeared. Moreover, there had high accuracy requirements of this system. It should be notedthat the curvature of sub-lens decides the collimated ability, the inclination of prism controls the scattered angle, and the center location of curvature affects the light field normal vector in horizontal direction.

To determine the floating image quality of this system, the light field distribution of each fan ray in vertical 45 degree was assumed as criterion, as shown in Figure 4(e). And the crosstalk values were calculated by the definition [6],

$$Crosstalk = \frac{\sum L_i}{L_0 + \sum L_i} \times 100\% , \qquad (5)$$

where the L_0 is the luminous of correct image and the L_i is the noise induced by the other fan rays' signal. As shown in Table 1, the maximum crosstalk value is about 22.9%, which is acceptable in the table-top floating image system.

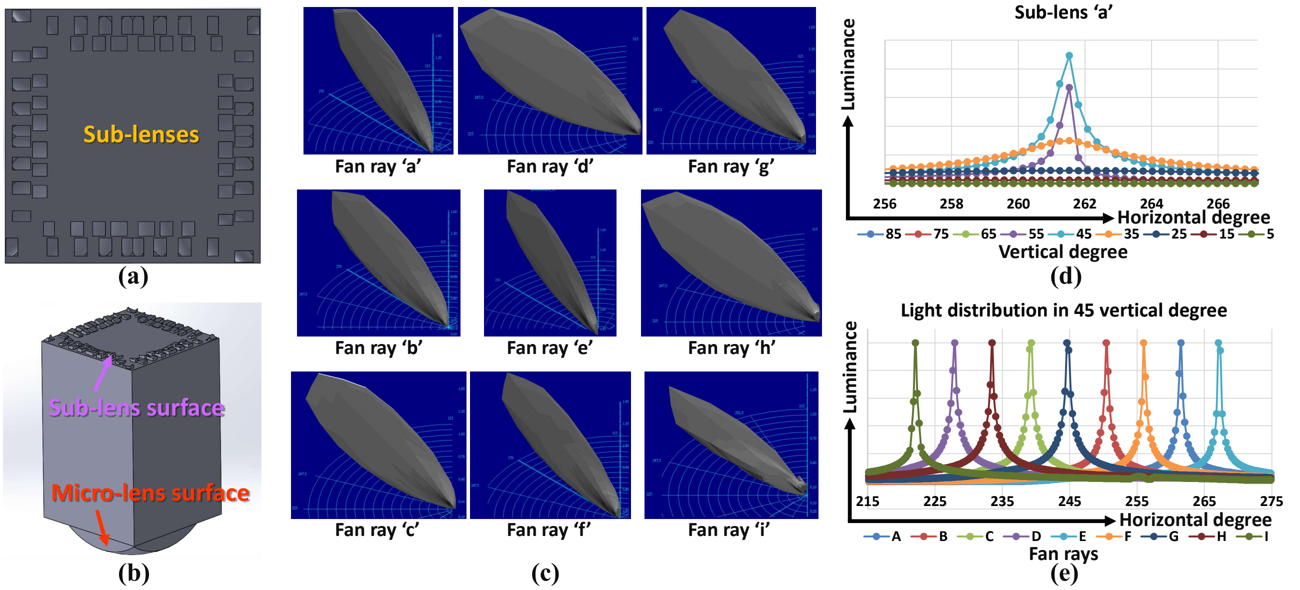

Figure 4. (a) Side view and (b) top view of repeatable freeform optical film unit; (c) Light shape of each fan ray; (d) light field angular data of sub-lens 'a'; (e) Normalized light distribution of different viewing zones in 45 vertical degree.

Sub-lens	a	b	c	d	e	f	g	h	i
Covered range	255.9°~267.2°	244. 7°~255.9°	233.4°~244.7°	222.2°~233.4°	261.6°~272.8°	250.3°~261.6°	239.1°~250.3°	227.8°~239.1°	216.6°~227.8°
Crosstalk	22.7 %	22.4 %	22.9 %	21.9 %	22.2 %	22.8 %	22.8 %	22.7 %	20.6 %

Table1. The covered ranges in the longitude direction and the crosstalk values of sub-lenses' fan ray.

4. CONCLUSION

In this paper, a new horizontal parallax table-top floating image system with freeform optical film structure was proposed. By this system, light field of each projector could be controlled as fan ray and the properties could be evaluated by simulation.For the hardware structure design, after passing through the Fresnel lens, every projected light would be changed as parallel rays and be controlled to focus in the corresponding positions by micro-lens surface of freeform optical film. Besides, on the top surface of optical film, the confocal concave structure with micro-lens would be chosen to collimate light in horizontal direction, and the prism shape was designed to scatter light field in vertical direction.According to the imaging principle and the inverse light tracking, the horizontal parallax floating image could be achieved by controlling the image signal of each fan ray. By the optical software simulation, the maximum crosstalk of each fan ray in the vertical 45 degree was 22.9%. Therefore, the table-top floating display with characteristics of high resolution, scalability, and without the noise would be achieved.

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