https://doi.org/10.2352/ISSN.2470-1173.2018.04.SDA-142

Full-parallax spherical light field display using mirror array

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Abstract

We propose a new optical system of glasses-free spherical 3D display and validity of the system is confirmed in this paper. The proposal display is light field display; a capable method to show 3D images to multiple viewers at once and perform complicated optical effect like occlusion effect. The proposal system is also capable to perform motion parallax effect in multiple directions (full-parallax). The proposal system is based on time-division multiplexing. The optical system consists of a rotating specially designed sphere-shaped flat mirror array and a high-speed projector. The rotating mirror array reflects rays from the projector to various angles. By controlling the intensity of the rays with the projector properly, a 3D image can be seen in the mirror array. From the results of the optical computer simulations using ray tracing method, expected 3D image was observed and we confirmed availability of the system as the 3D display. A prototype was developed using 3D printing and feasibility of the system was also confirmed. Additionally, color display of the same method was developed using 3 high-speed projectors.

Introduction

Various types of 3D displays have been studied actively. Because 3D images are attractive than 2D images, 3D displays observable with naked eyes are particularly expected to be used as digital signage. The wider viewing zone is, the more viewers can observe at once. Thus spherical or cylindrical displays which have wider viewing zone than flat ones, have the advantage in digital signage use. In addition, Sphere is suitable shape for 3D display to observe 3D image from various direction.

Some spherical 3D displays or wide viewing zone 3D displays were proposed previously. Spheree [1] is a 3D display using sphere-shaped rear projection screen and head tracking. In this method, 3D images can't be seen by multiple viewers. On the other hand, Perspecta [2] is a volumetric 3D display that can show 3D images to multiple viewers. Although it can't feature occlusion effect because volumetric displays can't block lights from light points behind the displayed object.

Light field displays; occlusion capable displays that reconstruct parallax rays, can provide 3D images to multiple viewers. One typical example of the display is century old integral imaging technology[3]. Because this method requires high-density lenses and pixels, a curved display like spherical one is difficult to achieve. Light field display using high-speed rotating mirror has special reflection property [4] can show 3D images to every angle around the display. However, this display can feature motion parallax effect optically only in horizontal direction. By using viewpoint tracking, vertical parallax is performed in the limitation of no multiple viewpoints are located in a same horizontal direction from the display.

The purpose of this study is to propose a new optical system to achieve full-parallax spherical light field display that multiple viewers can watch at the same time and features occlusion effect without head tracking. Full-parallax display performs motion parallax effect in multiple directions; displayed objects can be seen correctly from every direction.

Proposal method

Figure 1 is the scheme of the proposal display system. The system consists of a spherical mirror array, its rotation mechanism, and a high-speed projector. The high-speed projector generates rays and controls its intensity. The mirrors in the mirror array are flat and have different angles each other. The mirrors reflect rays to various angles. By rotating the mirror array, rays are scanned. By controlling the intensity properly, rays from displayed objects are reproduced in time-division average and 3D image can be seen inside the mirror array.

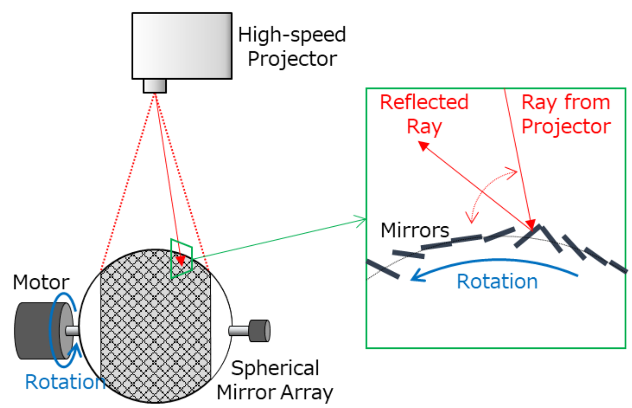


Figure 1. Scheme of proposal system

Spherical mirror array

The mirror array uniaxially rotates to scan rays. Figure 2 is the scheme of the array. The array rotates to direction φ, and direction θ is a vertical direction from direction φ and sphere normal. Angles φ and θ are similar to longitude and latitude.

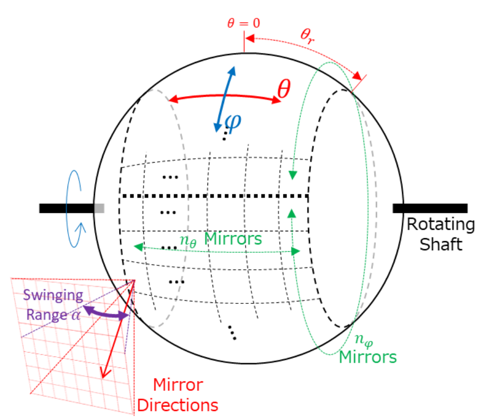


Figure 2. Scheme of mirror array

Mirror angle varies along direction φ to scan rays to a various angle by the uniaxial rotation. To display full-parallax image, mirror angles should vary to both 2 directions; up-down and left-right. n_φ, a number of mirror row along direction φ and α, swinging range of the mirror normal defines ray direction resolution. The resolution affects image quality and smoothness of parallax. For example, α=27[degrees], n_φ=100 to ray direction changes 10 stages at an interval of 3 degrees in both 2 directions.

The nearer to the rotation axis, the smaller mirrors are. Thus projecting to small mirrors requires pinpoint accurate projection, mirrors are only placed to the areas variable θ_r defines in figure 2.

The whole shape of mirror array should approximate sphere. Therefore, n_φ and θ_r roughly defines n_θ, number of mirror row along direction θ.

The size of display area per mirror array diameter is defined by mirror swinging range α. Figure 3 shows rays from point light source reflected on the spherical mirror. The mirror has modulated normal in range α=20 and 60. The display area is also shown in the figure because images is shown by the reflected rays in case of proposal method. The wider range α is, the larger display area is achieved.

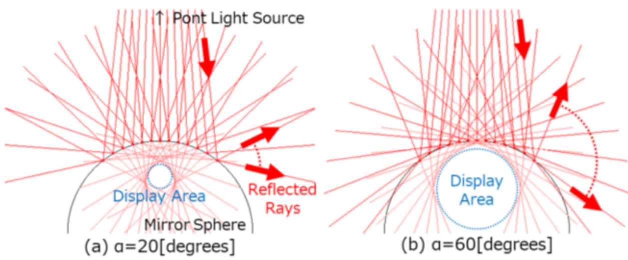


Figure 3. Reflection on spherical mirror has modulated normal

Rotation mechanism of mirror array

The rotation frequency is equal to refresh rate because rays once scanned by 360 degrees of the mirror array rotation. To prevent watchers from feeling flicker, mirror array's rotation must be high-speed. A rotary sensor is included in the mechanism to synchronize high-speed projector and mirror array rotation.

High-speed projector and projected image

Switching projected image corresponds to modulating the intensity of ray. Enough frame rate to follow rotating mirror is required for the projector. The lower frame rate leads the lower accuracy of ray intensity and the lower quality of the image.

The projection image is made based on ray tracing method. Figure 4 shows the process of making projection images. First, a model of projector and mirror array is prepared. Center rays of each pixel of the projected frame are traced to calculate reflected ray positions and directions. Second, the intensity of the each reflected rays is derived refer to the 3D data of the displayed object. Third, the intensity of rays is recorded to corresponding pixels of the projected image. This process is performed each angle of the rotation and projection image for each angle is generated.

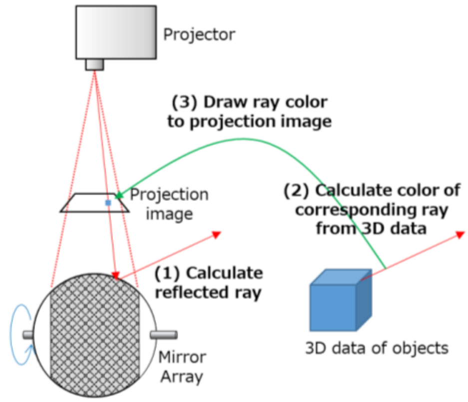


Figure 4. Process of generating a projection image

Computer simulations

Computer simulation of the display using open source ray tracing software POV-Ray is conducted to confirm availability of proposal method.

Simulation method

Table 1 shows parameters of the simulation. We modified POV-Ray to implement the functionality of generating projection images. Figure 5 (a) shows an image of mirror array design used in the simulation and (b) shows one of the projection images.

To simulate images shown in the system, motionless temporary images of mirror array stopped in each angle is generated by POV-Ray first. By calculating the average image of the temporary images, an image generated by high-speed rotating mirror array is observed. The display area in the average image is amplified to observe displayed image because ray intensity of projector is higher than diffused ambient lights.

Thus pinhole model of projector is used in the simulation, the mirror array must slightly diffuse rays from the projector to show an image. We use Phong specular reflection model as reflection model of the mirror array to simulate slightly diffusing mirrors.

Table 1 Parameters used in the simulation

Spherical mirror array	
Radius	300[mm]
Number of mirrors	3000 (n_θ=30,n_φ=100)
Swinging range of mirrors	α=30 [degrees]
Range of mirrors	θ_r=45[degrees]
Reflection model of mirror	Phong specular reflection model (shininess constant = 1000)
Projector	
Position	1000[mm] above the center of the mirror array
Field angle (diagonal)	30[degrees]
Projection image size	1024×768[pixel] (XGA)
Number of projection images per rotation	360
Projection object	Dice (40[mm] each side)
Other	
Number of temporary images from POV-Ray per rotation	1000

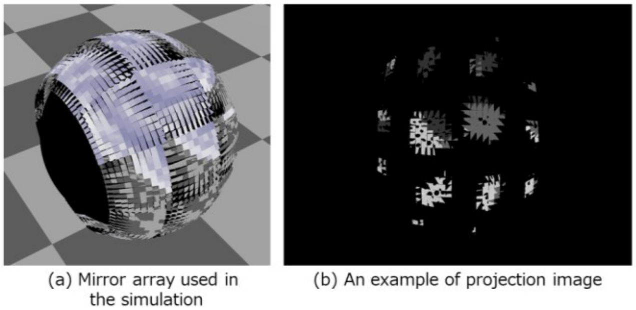


Figure 5. Details of simulated system

Simulation result

The 3D image observed from several angles are shown in figure 6 (a) and ideal image of the displayed object looking from same angles are shown in figure 6 (b). This result shows that the system is available as the 3D display.

However, 3D image is blurred because of lack of ray accuracy. The reasons for the low accuracy are considered to be diffuseness of mirror array and discrete translating of the frames projected to continuous rotating mirror array.

Black lines are also observed on the 3D image. This is because of existing mirrorless area or shaded area by other mirrors on the mirror array.

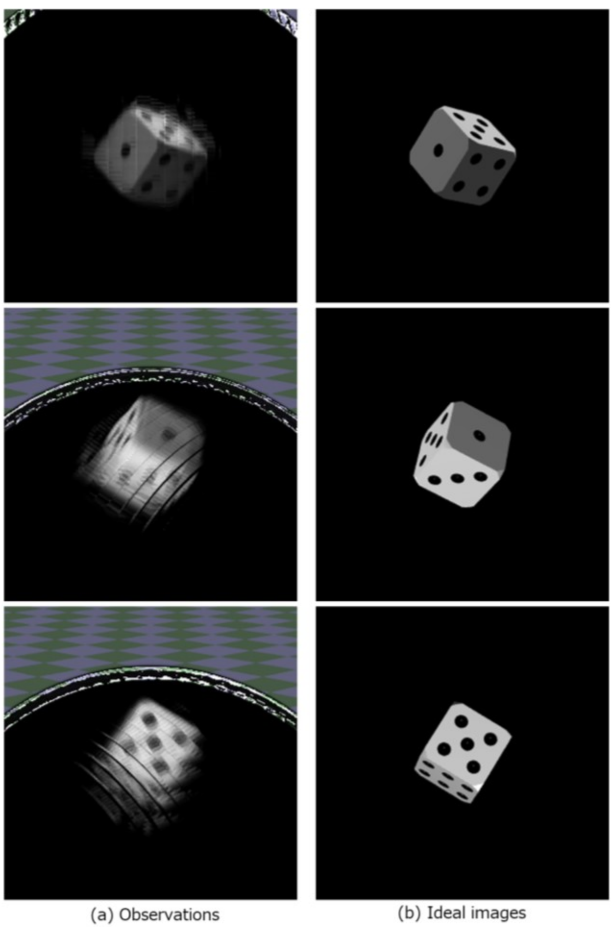


Figure 6. Simulation results

Experiments using prototype

A prototype is developed to confirm the feasibility of proposal system. Also, color display using red, green and blue projectors is developed.

Prototype development

Monochrome display

The photo of the monochrome prototype is shown in figure 7 and specifications of its high-speed projector are shown in table 2. The design of the mirror array is same as table 1. To adjust diffuseness of the mirror array, diffuser sheet is placed above the mirror array. The refresh rate was 20 Hz and the rotation rate of the mirror array was set to 1200 RPM.

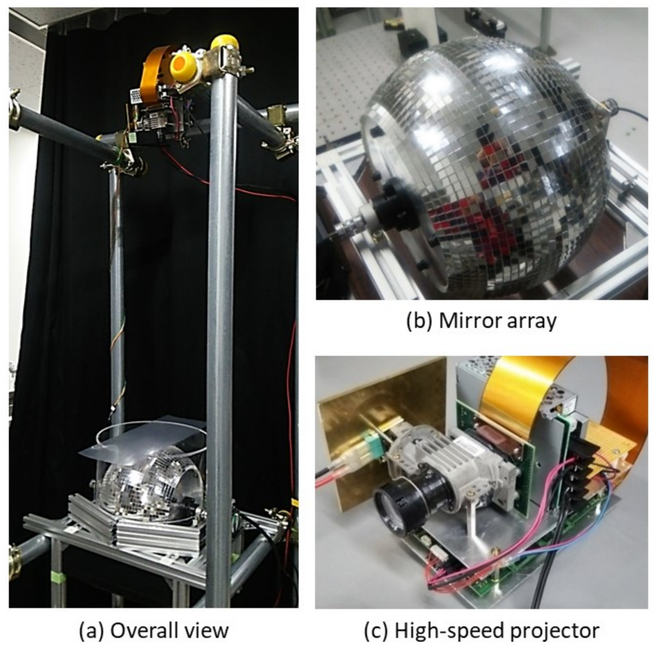


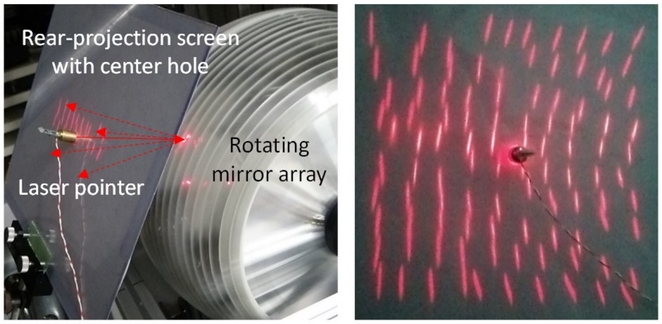
Figure 7. Monochrome prototype

Table 2 Specification of the high-speed projector

DMD module : ViALUX V-7001 Projection optics : ViALUX STAR-07 CORE	
Projection image size	1024×768[pixel] (XGA)
Field angle (diagonal)	33.8[degrees]
Framerate	22,727[Hz] (Binary)

Plastic powder lamination 3D printer was used to shape the mirror array and polycarbonate mirrors were placed by hand. The errors in mirror angles were measured by the method shown in figure 8. This method uses reflection pattern generated by hitting straight laser light to the speedy rotating mirror array. The reflection pattern is projected to a rear-projection screen with center hole emitting laser light vertically. The pattern is captured by camera and perspective correction is conducted.

The number of reflection pattern is n_θ and there is n_φ of light spots in one reflection pattern. The light spots are identically placed in a square with pincushion distortion. This ideal pattern is used to calculate the amount of error. The pose of the screen is estimated on the assumption that amount of error is minimum, then mirror angles are estimated from the pattern. Database of mirror angles is updated to estimated angles then projection images are regenerated.



(a) Measuring reflection pattern (b) An example of reflection pattern

Figure 8. Measuring mirror angles

Color display

Normally DMD color projector uses time-division multiplexing to color projection with rotating color wheel. In the case of a proposed method, high frame-rate is required for the projector and time-division multiplexing is difficult to be used to color 3D image. We use 3 high-speed projectors to generate each red, green and blue rays.

Thus optical axis is different in each projection in this structure, calibrating each projector according to projection image is more difficult than single projector located above the center of the mirror array. We placed flat screen above the mirror array and project specific image for calibrating from every 3 projectors. The pattern has numbers of crosses and those indexes. The pattern on the screen was captured and perspective corrected, then projector pose is estimated from the position of manually located and identified crosses on the calibration image. Then, projection images were made according to the estimated pose.

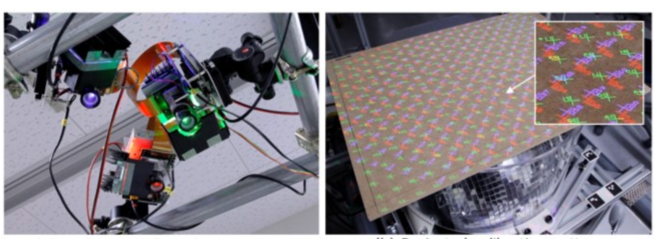

(a) 3 projectors for color projection (b) Projected calibration pattern

Figure 9. Details of color display

Experimental results

Figure 10 is displayed objects and the 3D image observed in the prototypes is shown in figure 11. Full-parallax images were displayed in the prototype and we confirmed the feasibility of the display. The color prototype also successfully showed a color image.

However, the 3D image displayed in the prototype was not consistent in brightness. Especially the areas near rotation axis show a blurred image. This phenomenon is traceable to the difference of diffuseness between simulation model and the prototype. Mirrors near rotation axis are farther than the others from the diffuser. It is considered that using hemispherical diffuser shell having appropriate diffuseness solve this problem.

In addition, colors were incorrectly observed occasionally in color prototype. This is because of the difference in ray directions of each color; transition of parallax shifts between colors.

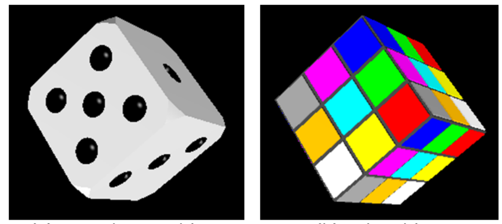

(a) Monochrome object (b) Color object

Figure 10. Object displayed in the experiment

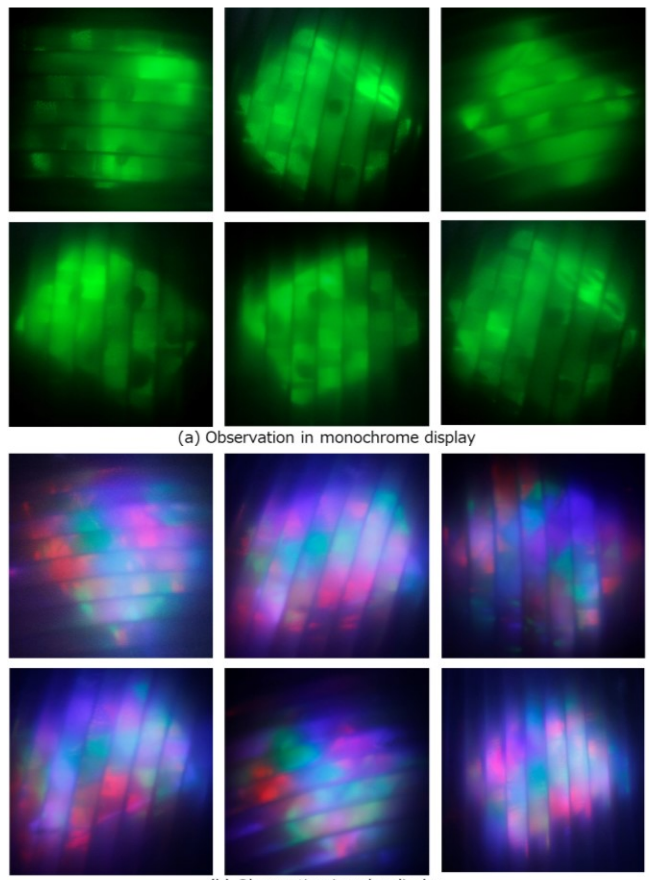

(a) Observation in monochrome display
(b) Observation in color display

Figure 11. Experimental results

Conclusion

A new optical system of spherical full-parallax light field display was proposed in this study. Computer simulation of the system was conducted. From the result of the simulation validity of the system was confirmed. Although, 3D image quality was low because of lack of ray accuracy and shape of the mirror array. A prototype of the display was developed and from the result of experiments, the feasibility of proposed method was confirmed. However, the displayed image was not consistent in brightness because of mirror array diffuseness adjustment. By using 3 projectors, color display of proposed method was also achieved. Occasionally colors incorrectly observed because of projection optical axis difference.

Redesigning of mirror array for better image quality or enlarge the area of view will be done in the future work.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Numbers JP15KK0004, JP16K12475, JP17H01776.

References

[1] Fernando Teubl Ferreira ,Marcio Cabral ,Olavo da Rosa Belloc, et al. "Spheree: A 3D Perspective-Corrected Interactive Spherical Scalable Display", SIGGRAPH, Vancouver, 2014.

[2] Gregg E. Favalora ,Joshua Napoli, Deirdre M. Hall, et al. "100 Million-voxel volumetric display", Cockpit Displays IX: Displays for Defense Applications, proc. SPIE vol. 4712, pp. 300- 312, 2002.

[3] Gabriel Lippmann. 1908. Epreuves reversibles donnant la sensation du relief. J. Phys. Theor. Appl. 7, 1 (1908), 821–825.

[4] Andrew Jones, Ian McDowall, Hideshi Yamada, et al. “Rendering for an Interactive 360° Light Field Display” ACM Transactions on Graphics, vol.26, no.3, article 40, 2000

Author Biography

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