3-6 fVisiOn: Glasses-Free Tabletop 3D Display Observed from Surrounding Viewpoints of 360°

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This paper describes a novel glasses-free 3D display of 360° optimized for tabletop tasks. For sharing 3D virtual objects on a flat tabletop surface naturally, we assume that the following conditions should be satisfied: (1) the tasks should not be disturbed and the working spaces should not be occupied, (2) the 3D images should be observed from arbitrary directions around the table, and (3) special 3D glasses should not be required for natural communication around the table. In this paper, we propose and implement the 3D display "fVisiOn" which fulfils the above whole conditions. The display employs circularly arranged projectors and a cylindrical- or a conical-shaped optical device that has a directional optical characteristic. Those devices are installed underneath the table not to obstruct the working space. One of the novelties of the proposed method is forming a ring-shaped viewing area above the table. When users look in this area, they can observe individual 3D images from each direction with correct perspective on the table such as a centerpiece.

Keywords
Glasses-free 3D display, 3D images, Light field reproduction, Tabletop, Collaborative work

1 Introduction

In this paper, we propose an innovative glasses-free 3D display. This study assumes scenes where several persons sit around a table and share some information on the table for collaborative work, such as in conferences as illustrated in Fig. 1. In such situations, participants would proceed with discussions by exchanging documents and sharing product mockups placed on the table. The method described in this paper is designed for providing virtual 3D objects beside the real objects naturally in such scenarios on the table.

The system named "fVisiOn" is a prototyped tabletop 3D display by using our 3D image reproduction principle. The fVisiOn can float raised 3D images on a flat surface on the table; the 3D images appear on top of the table without any display devices in an area above the table. Its suitable observation area is specifically designed for seated conditions around the table, and the produced virtual 3D objects are available for omnidirectional viewing of 360°. The system is intended to become a friendly interface that many participants can use naturally without the use of special 3D glasses. Therefore, it has a potential for promoting communication via a table. Figure 2 shows the results of 3D images reproduced with the prototyped system.

The proposed method[1]–[4] reproduces 3D images by employing a hundred of projectors arranged in a circular manner and a cylindrical or conical optical device having an anisotropic optical characteristic. In our principle, the entire mechanism of display devices is installed below the tabletop. Therefore, there is no object to interfere any tasks on the table physically; this means that the participants can use

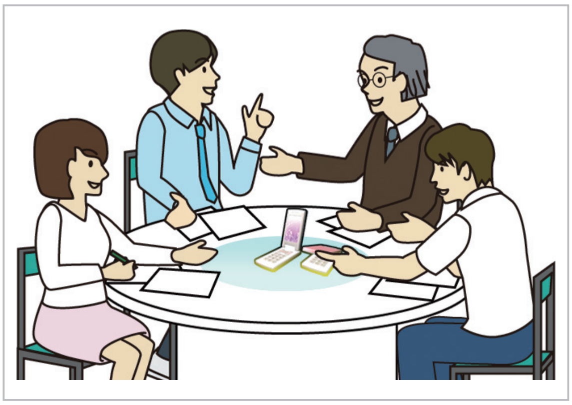


Fig.1 Conceptual illustration of our tabletop 3D display

Fig.2 Glasses-free tabletop 3D display, "fVisiOn"

the space of the tabletop freely. The optical device controls the flying paths of numerous rays produced from the projectors, as if to reconstruct rays that should be emitted by the surface of the object—assumed to be in the center of the tabletop—and reproduce 3D images viewable from arbitrary directions all around.

This paper first describes the characteristics of tabletop work, and then discusses the forms of 3D displays best suited for those characteristics. We then propose a new form of 3D image presentation method that meets the requirements discussed and state the necessary functions of optical device. For developing the 3D display, a method to fabricate an optical device having the required functions is introduced and its prototype is mounted as a part of the system. Finally, the system demonstrates the proposed 3D image reproduction method which allows people to actually observe 3D images of 360-dgree view without the 3D glasses[5][6].

2 3D images for tabletop work

2.1 Characteristics of tabletop work

Since ancient times, people have been using tables and desks as places for doing some kind of work. A desk is considered a tool that reminds people of uses rather personal, while a table is believed to serve as a place for several people sitting around it to communicate. The area on top of the table, called tabletop, allows people to put any objects there. Therefore, the system of the tabletop stores the work temporarily, arranges the necessary information, or performs other work, thereby making effective use of expanded space so that people can work more smoothly. The tabletop can also be used as a tool for information sharing and collaborative tasks, including handing a work object over to other persons around the table or engaging in debate while sharing the object.

If a tabletop offering such user-friendliness were to be used as a computer-supported interface between the virtual world and the real world, and we regarded it as a place for interpersonal or human-computer interaction and for exchanging and sharing information, then it will be important to realize a mechanism as an interface for presenting effective information, understanding user intentions, and proceeding smoothly with collaborative tasks.

When we consider the tabletop as an interface, providing information with a visual medium is important for making it easier to understand and convey. Consequently, many computer-supported interfaces have been proposed, including overlaying visual information on a tabletop by using an overhead projector, and thus providing assistance in work[7]. Moreover, when many people around the table use the system, it is also important to provide appropriate perspective images that look differently depending on respective viewpoints and viewing directions[8]. Here, particular attention is required when selecting 3D imagery as a visual medium to be shared: that is, it is desirable to utilize a method that does not adversely affect work performance or the tabletop's original value as a communication tool.

In other words, when we consider handling a visual medium on a tabletop in an even more natural form and in a 3D manner, the method must: (1) not occupy space on the tabletop so as not to interfere with collaborating tasks, and (2) enable the observation of appropriate perspective images from around the table in arbitrary directions. It is also desirable to: (3) provide an observation system that requires no special 3D glasses and does not limit the number of participants for casual discussions.

2.2 Related works

Several 3D displays that partly adopt the above concepts have already been proposed. The following describes those related works and discusses the differences between them and our work.

2.2.1 Volume-swept display

There are many 3D displays designed for all-around observation without the 3D glasses. Those systems generally have a moving mechanism for reproducing 3D image and are roughly divided into the volumetric display type[9], multi-view display type[10], and light field display type[11][12]. Those systems are designed to present appropriate images and light fields according to the voxel value and viewing direction, while in synch with the direction of the moving mechanism, such as a screen like a rotary disc.

These systems thus satisfy conditions (2) and (3) above, but each system requires a comparatively large-scale mechanical device on the table. As a result, most of the tabletop area will be occupied, thereby limiting the uses of space as a place for collaborative work and resulting in failure to satisfy condition (1). Moreover, reproduced 3D images are in a state as if being contained in a glass showcase, so that viewers cannot interact directly with the 3D images and it is difficult to feel that there were a 3D image on the table which they could almost hold in their hands.

2.2.2 Floating image display

One proposed system involves using mirrors or other ingenious devices with the optical system to relay the real image of an object that exists somewhere in the air. Several methods have been proposed, including the relay of real images by using two opposing concave parabolic mirrors, which is a well-known classic illusion, along with a system based on a lens system[13], and one based on transmissive mirror devices[14]. Another proposed system employs several mirrors to relay images optically in the air, thereby allowing people to observe several directions' worth of 2D images from the corresponding direction[15]. These systems let people see the real image relayed in the air, and allows them to have a highly realistic feeling. However, if the source object is a 2D image such as one on an LCD, the produced floating image will likewise be a 2D image. Displaying a 3D image electronically requires another 3D display at the source, making it difficult to constitute a 3D display in isolation.

Another proposed system involves applying high energy to certain points in the air, thereby causing the air molecules to emit light[16]. Actually touching the resulting 3D image is currently impossible due to safety reasons, and cannot be used as a tool for collaborative tasks. Yet another proposed system involves projecting images onto smoke or water steam[17], but this constitutes the display of 2D images in the air, and not 3D images.

2.2.3 Tabletop display corresponding to multiple viewers

Some systems do not need a display device above the table in order to satisfy condition (1). One system allows several people to observe 3D imagery from different directions at the same time by tracking their viewpoints and using 3D glasses[18], and another system allows people to observe separate 2D images from four directions[8]. Each system is similar in terms of concepts presented in this study, but each is also limited to about four observers. The former system requires observers to wear 3D glasses in observing 3D imagery, while the latter involves 2D imagery.

2.2.4 Flat panel 3D display

The 3D imagery reproducing methods by electronic holography[19] and integral imaging[20] satisfy condition (1) because they involve a flat display surface that serves as a mechanism for displaying 3D imagery. It also enables no-glasses observation to satisfy condition (3).

In those methods, a region suited for observation, called viewing area, is limited to a narrow range in the perpendicular direction of the display surface. Thus those systems suit for observation style such as watching ordinary TV. Its stereoscopic feeling is also basically nothing but a one-directional depthwise expression regarding the display surface; 3D imagery is inapplicable to observation from 360 degrees where people go around and view the object from behind.

When such flat panel-type 3D display is placed horizontally on the table and employed as a principle, wider viewing area to meet the needs of all-around observation for the tabletop use is required. However, the viewing area of electronic holography is currently only a few degrees, and even integral imaging systems only cover dozens of degrees. Therefore, under the tabletop scenario, i.e., looking down the display from a slanting oblique direction above, the designed viewing area of such 3D display, almost in front of the display, cannot be used effectively, and the use of edgewise region of the optical device makes reproducing 3D imagery difficult because it generally does not perform appropriately.

As an example, a glasses-free tabletop 3D display based on integral imaging has been proposed[21]. This system is suited for observation where the observer views an image from top of the display. However, observation from around the table as seen in seated scenario is not assumed for such 3D displays and its viewing area does not work effectively. Conversely, another integral imaging-based system optimized its viewing area for a particular oblique direction in a horizontal position[22]. However, its viewing area is limited in a small area and it cannot provide 3D images for many people to observe from around the table. Therefore, this technology fails to satisfy condition (2) as well.

2.2.5 3D imagery by fVisiOn

Our new approach involves arranging all the mechanisms for reproducing 3D imagery underneath the table surface, thereby securing a working area on the tabletop to satisfy condition (1). In our reproduction principle, we define a ring-shaped viewing area above and around the table to satisfy condition (2), and reproduces 3D imagery at the center of the tabletop can be observed from arbitrary directions of 360 degrees without the 3D glasses that satisfies condition (3).

Here, the assumed observation style of fVisiOn is a seated or standing viewing condition; this generally involves no large vertical movement of viewpoints and not designed for observation from right overhead of the table. These forms are characterized by resolving individual limitations found in related works, obviating the need for special equipments for the users, allowing many people to observe 3D imagery from around the table simultaneously, and not interfering with ordinary interactive tabletop work.

3 Light field reproduction for tabletop work

3.1 Reproduction of imagery by simulating lighted scene

Our proposed 3D image reproduction method is based on optical simulation of a real lighted scene; eyes shall catch lights scatted on each object's surface in the scene. In the followings, we describe our principle by considering opaque objects in the real world as a simplified model.

Light emitted by a light source are diffuse-reflected on each surface of any objects in the scene. When both eyes catch the light scatted on the surfaces, we perceive the objects in the scene. In geometrical optics, we can assume that a point light source produces innumerable beams of light, i.e., rays, traveling in all directions. When we focus on a certain point on the surface of an object, we can assume that uncountable rays are incoming from light sources at the point. Then, according to the diffuse-reflection property on the surface, uncountable rays are outgoing in all direction. This situation is considered that there is a virtual point light

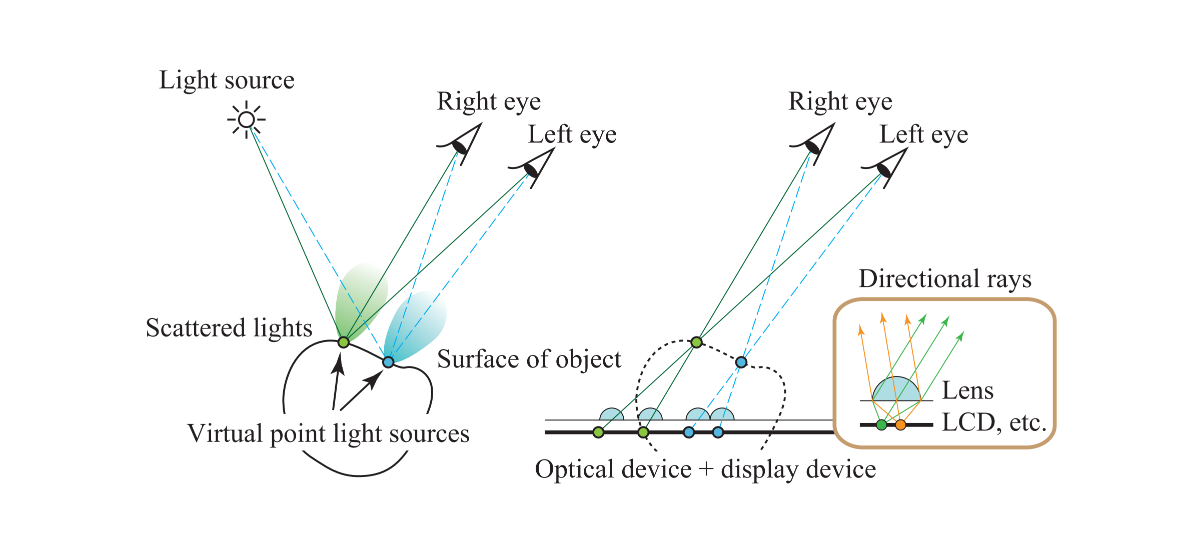


Fig.3 *Principle of light field reproduction*

source at the point (Fig. 3, left). In other words, by producing a group of rays passing through that location, and applying the appropriate light property of color and luminance that meet the direction of passage, the rays should simulate the lighting conditions of the real scene and produce 3D imagery of any objects.

Convex lenses and other optical devices are candidates to control orientation of the rays. It condenses rays from a point light source at the focal length, and then radiates the rays in parallel with a straight line passing through the point light source and the principal point of lens. As a result, when a display device, such as an LCD, is arranged under the concave lens, a group of rays radiated from a certain pixel arranged in a 2D manner will be observed only from the corresponding directions.

We can thus determine the direction of a traveling ray based on a positional relationship between the pixels on the display device and the optical device. When calculating the intersection of a certain ray and the assumed surface of any objects in the scene, we can compute the color and luminance that should be emitted by the point along the direction of the ray. By preparing numerous virtual point light sources by rays in space, the assumed surfaces of the objects are reproduced (Fig. 3, right).

If a particular space is fulfilled by infinite rays orients all direction accurately and densely, a complete state of light in the space is described as a light field and it can simulate a condition of the real scene. When observing the light field from separated viewpoints, different images can be obtained because it stores omnidirectional rays. This means the light field provides binocular disparity for both eyes and it produces depth perception for the observer. Here, the method to reproduce 3D imagery by preparing such a light field is named the light field reproduction.

3.2 Viewing area required for tabletop work

In this study, we introduce an assumption that the 3D image on a tabletop is constantly observed obliquely from above for optimizing the tabletop scenario. In this condition, the viewing position is determined to the circular region obliquely above the table, and only the group of rays that reach the region should be considered. Moreover, as a cue of depth perception, simply reproducing binocular disparity in the circumferential direction of the table should suffice.

As shown in Fig. 4, we take origin O at the center of the tabletop, consider the X-axis and Y-axis (mutually orthogonal on the flat tabletop), and define the space vertically above O as the Z-axis. At this time, if the user observes the object at a distance of e_d from the table center and from a height of e_h, then the circle expressed by $E = (e_d \cos\theta, e_d \sin\theta, e_h)$ will be defined as the viewing area. Note that θ is an angle based on the X-axis around the Z-axis, and represents an arbitrary viewing direction.

Here, let us consider the group of rays that should be reproduced, on a certain plane, which crosses the X-Y plane vertically, such as the X-Z plane. As illustrated on the left in Fig. 5, in such plane, the ring-shaped viewing area is projected as two points above on both sides sandwiching the table, and the group of rays to form an image should pass the points at least. As also depicted in the figure, the ordinary integral imaging method will form a viewing area in the range of dozens of degrees in the Z-axis direction; the group of rays fills in an upper area. That area will not be used as viewpoints in the assumed forms of tabletop use. For matching the assumed viewpoint, such method should expand its viewing area extremely wide.

The necessary rays on the X-Y plane must be defined as a group of rays concentrated in a radial manner from a certain region of the tabletop toward an arbitrary point E in the ring-shaped viewing area as shown in Fig. 5, right. When the observer puts both his/her eyes on this circular area, a pair of different retina images will be perceived, resulting in stereoscopic sight.

3.3 Reproduction of necessary rays by directional optical device

As the means of generating the necessary rays for our reproduction principles, this paper proposes a method employed a cylindrical or conical optical device and an array of projectors installed underneath the table

The optical device works as a rear projection screen having a special anisotropic optical function, so we call it screen simply, here. The rays produced from the light source of the projectors are given different light properties by passing a spatial light modulator such as an LCD. This can be approximated that rays scat-

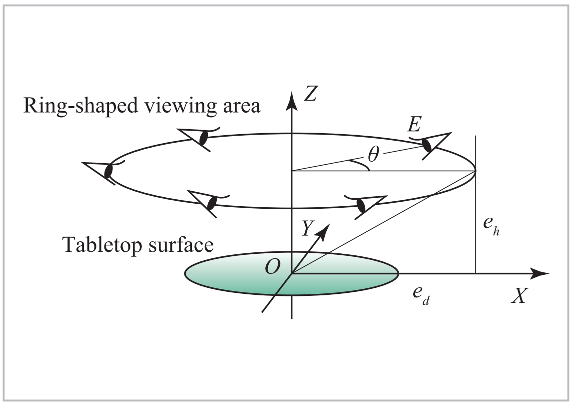


Fig.4 Viewing area defined by our proposed method

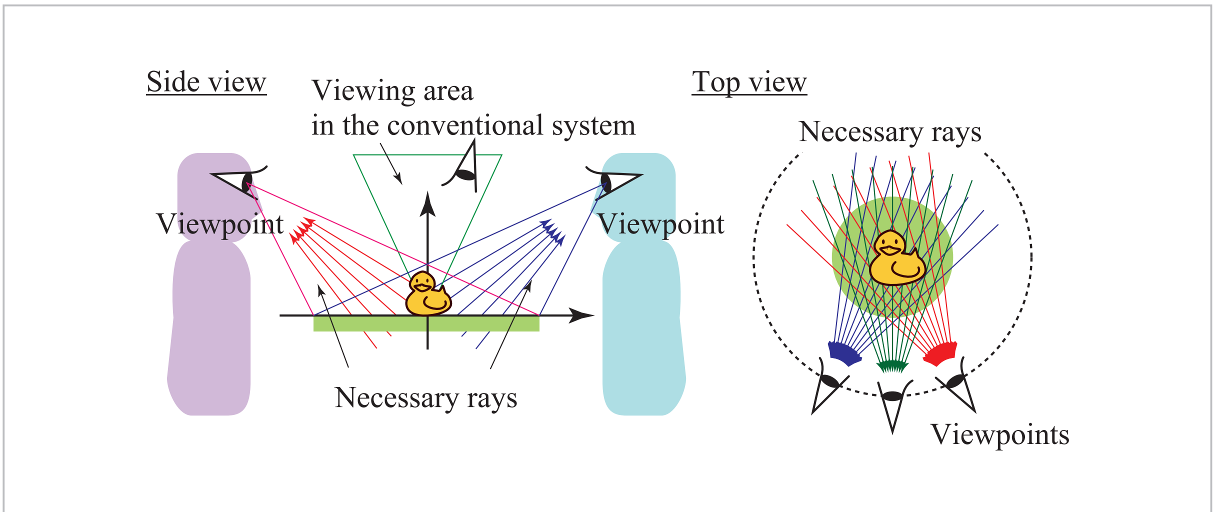


Fig.5 Necessary rays for observation from around the table

ter in a radial manner with a certain color and luminance from the projection center. Figure 6 depicts several projectors arranged on a circumference below the table surface that project images to the side of the screen. Here, a conical screen is shown as an example. This screen offers a directional optical function; it scatters the passing rays in the ridgeline direction and makes the rays go straight in the circumferential direction instead of scattering. This configuration results in the ray state shown in Fig. 5 according to the following procedure

In the plane that crosses the *X*-*Y* plane vertically (as similarly shown on the left in Fig. 5), each ray produced from any projectors will be scattered at a certain angle only in the vertical plane after passing through the screen. At that time, we can only observe scattered rays directed toward the viewpoint.

In contrast, in the *X*-*Y* plane, the screen lets rays pass in a circumferential direction, so that the rays projected by the projectors arranged in a circle will continue going straight after passing through the screen. As a result, a certain group of rays reaching any viewpoints will be an integration of the rays emitted from the different projectors as shown in Fig. 6, right.

When projectors are installed at sufficiently short intervals and each ray is given an appropriate light property, then it is considered that we will perceive 3D imagery on the basis of the principles of the light field reproduction.

4 Prototyping and experimentation for verifying the principles

4.1 Prototyping of optical device

We fabricated a conical screen having the abovementioned function as a prototype optical device. Here, we propose a fabrication method by attaching a filament lens on the side of a conical body based on the concept described below. First, the cross section of the filament is a circle, thereby obtaining optical effects similar to those of a ball lens, and the incident rays will presumably pass through its focal point and exit in a radial manner. In contrast, in a lengthwise cross section, this can be regarded as a transparent body having a certain thickness, while the incident rays will only become refracted twice and travel in parallel. If the path in the lens is quite short, the rays would travel almost straight.

In this prototype, we employed a nylon fishing line as the filament lens. We applied ultraviolet curable resin to the side of a cone (i.e., upper bottom of 200 mm, lower bottom of 20 mm, height of 110 mm, side thickness of 2 mm) cut from an acrylic block, and then wound a fishing line (0.4 mm in diameter) around the cone, while subjecting it to ultraviolet rays.

Figure 7 shows results when laser beams of

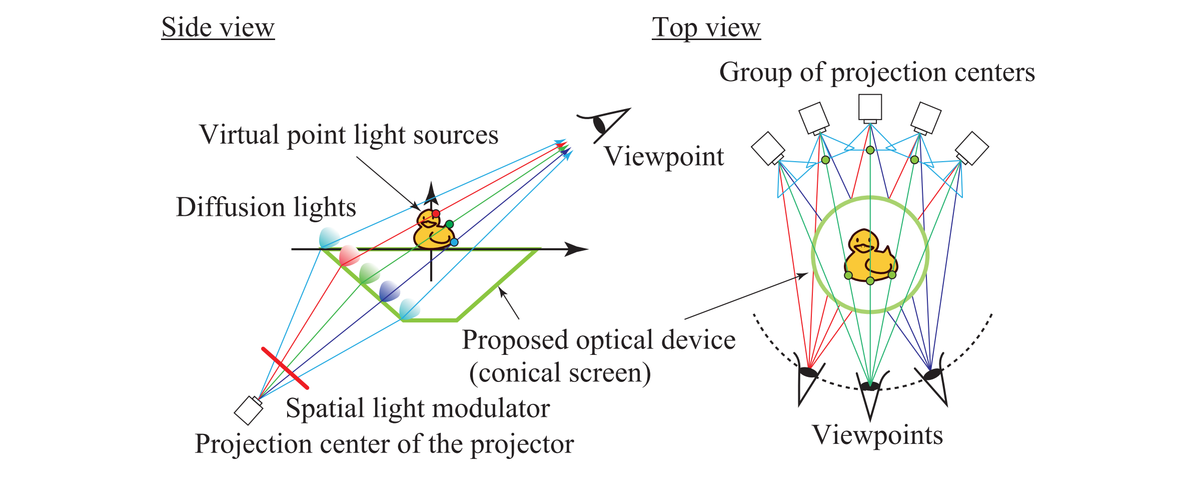


Fig.6 *Proposed generating method of necessary rays*

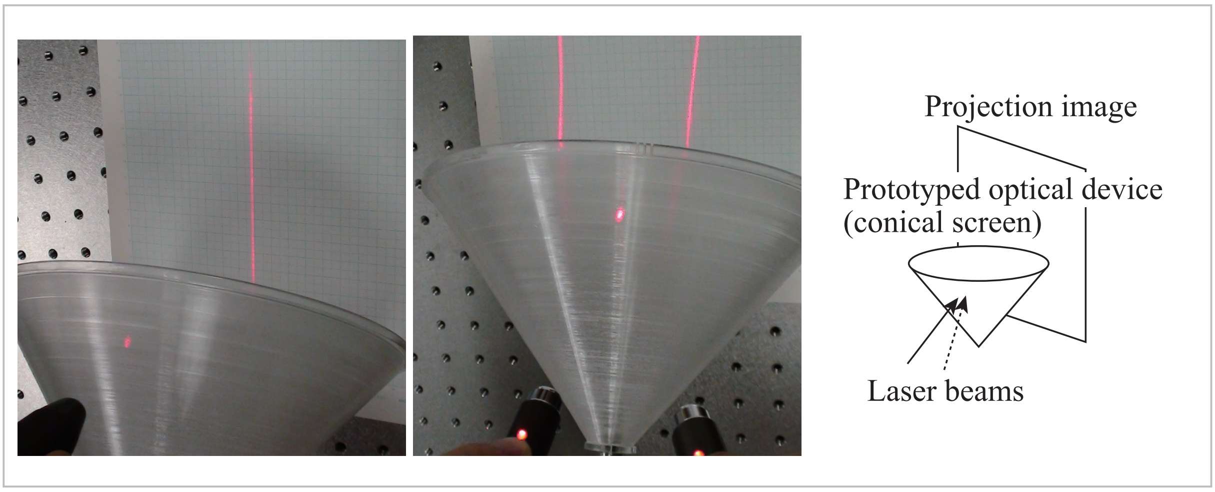


Fig.7 Optical function of the prototyped screen (left, diffusive; right, going straight)

1 mm in diameter were cast on the prototyped screen and its outgoing beams were projected onto a sheet. As a result of entering one laser beam, we observed performance where the material diffused the beam at about 60 degrees in the ridgeline direction and at about 1 degree in the circumferential direction. Moreover, as a result of entering two laser beams at the same point from different directions, we observed performance where the beams were little diffused and traveled almost straight out in the circumferential direction.

4.2 Results of reproduced 3D images

We employed the prototyped screen and 96 micro LCD projectors (VGA, 8 lm) and displayed 3D imagery by using the proposed light field reproduction. Figure 8 shows several results of the reproduced 3D images. From the top row, the figure shows examples of a reproduced teapot, a toy duck, and a rabbit. An actual *origami* crane accompanies the rabbit for reference.

Here, the interval between projectors is 15 mm, with the projectors located in a radius of 676 mm from the origin, and 535 mm below.

The ring-shaped viewing area has a height e_h of 340 mm above the tabletop and a distance e_d of 500 mm from the table center.

The projection images from each projector were prepared by using a ray-tracing algorithm. First, we determined the ray emitted from the optical center of the projector and directed towards each pixel of the spatial light modulator, and then computed the intersection of the ray and the screen. Next, we determined a straight line from the intersection on the screen in the horizontal direction and toward the ring-shaped viewing area in the vertical direction, and then determined the intersection on the side closest to the viewpoint between the straight line and an assumed surface of any objects. As the light properties given by the spatial light modulator on the pixels, we gave a color and luminance to be reproduced by the virtual point light source at the intersection on the object's surface in the direction of the straight line.

Each set of three photos was photographed directed toward the table center from respective positions varied by 50 degrees in the ring-shaped viewing area. From each set, we obtained results of different perspective observations, thereby confirming that parallax was obtained on the horizontal surface.

5 Conclusion

This paper proposed a glasses-free tabletop 3D display "fVisiOn" suited for tabletop work and described its prototyping. We proposed a method of forming a ring-shaped viewing area around and above the table with light field reproduction, and a method of fabricating an optical device having the necessary functions. We

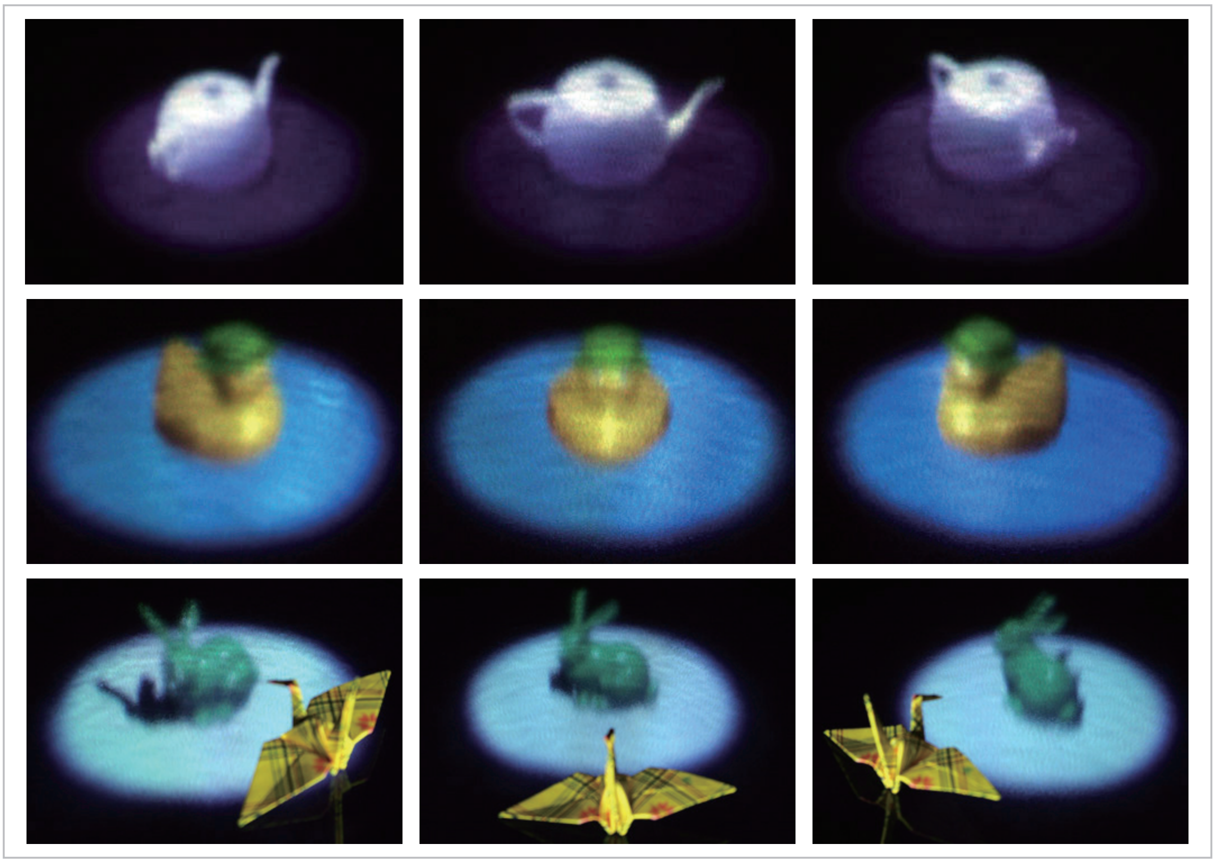


Fig.8 *Observation results from different viewpoints of a reproduced image*

also reproduced 3D imagery by using the prototyped optical device and confirmed that the ring-shaped viewing area enables stereoscopic viewing. This system is characterized by a viewing area arranged circularly around and above the table, and parallax as obtained circumferentially.

The present implementation succeeded in constructing a system viewable from 120 degrees. Although it is one-third of being ideal, the system can be adapted to 360-degree observation in principle. Moreover, although the imagery obtained in this experimental environment is still unclear, this would be due to inadequate performance of the prototyped optical system or the orientations of the rays reproducing the imagery might include a computational error relative to the theoretical value. Improvement of the image quality is another challenge to be addressed in the future.

References

1 Yoshida, et al., “A Primal Study of Auto-stereoscopic Display for Tabletop Tasks VRSJ,” The 14th Annual conference of VRSJ 2009, 3A4-4, 2009.

2 Yoshida, et al., “Implementation of Auto-stereoscopic 3D Display for Tabletop Tasks,” ITE Tech. Rep., 33(42), 3DIT2009-72, 33–36, 2009.

3 Yoshida, et al., “Glasses-free Table-style 3D Display Observed from Surrounding Viewpoints - A Study of Displaying Principle and Prototyping -,” Transactions of the Virtual Reality Society of Japan, 15(2), 121–124, 2010.

4 Yoshida, et al.,: Prototyping of Glasses-free Tablestyle 3D Display for Tabletop Tasks, SID2010, 211–214, 2010.

5 Yoshida, et al., “Glasses-free Tabletop 3D Display Using Light Field Reproduction for Omnidirectional Viewing,” 3D Image Conference 2010, 51–54, 2010.

6 Yoshida, et al., “Implementation of a Table-style 3-D Display Based on Light Field Reproduction,” ACM SIGGRAPH2010, Poster 45B, 2010.

7 Koike, et al., “Enhanced Table”, PCM2004, pp. 97–104, 2004.

8 Kakehi, et al., “Lumisight Talbe,” IEEE CG&A, 25(1), 48–53, 2005.

9 Actuality Systems, Inc. “Perspecta Spatial 3-D System,” http://actuality-medical.com/, 2002.

10 Otsuka, et al., “Transpost: all-around display system for 3D solid image,” VRST’04, 187–194, 2004.

11 Jones, et al., “An interactive 360° light field display,” SIGGRAPH2007 E-Tech, 13, 2007.

12 Ito, et al., “360-degree Autostereoscopic Display,” SIGGRAPH2010 E-Tech, 2010.

13 Ishikawa Optics&Arts Corp. : ILLUSION THEATER etc., http://www.holoart.co.jp/, 2009.

14 Maekawa, et al., “Face-toFace Communication System with Floating Image,” 3D Image Conference 2009, 149–152, 2009.

15 Wada, et al., “FloasionTable: Multidirectional Tabletop Floating Vision System for Mixed Reality Exhibition,” IEICE Tech. Rep., MVE2009-135, 29–34, 2010.

16 Kimura, et al. “Laser produced 3D display in the air,” SIGGRAPH2006 E-Tech, 20, 2006.

17 IO2Technology: Heliodisplay, http://www.io2technology.com/, 2009.

18 Kitamura, et al., “A Stereoscopic Display for Multiple Users with Polarization Filters,” IEICE TRANSACTIONS on Information and Systems, J90-D(10), 2893–2902, 2007.

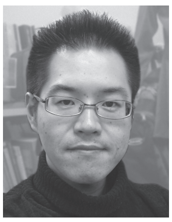
19 Mishina, et al., “Three-dimensional color image reconstruction by electronic holography using ultra-high-definition liquid crystal displays,” HODIC, 30(2), 12–17, 2010.

20 Arai, et al., “Microlens arrays for integral imaging system,” Applied Optics, 45(36), 9066–9078, 2006.

21 Sakai, et al., “Large Integral Photography Display Based on Overlaid Projection Method Using Mini-Projector Array,” 3D Image Conference 2009, 165–168, 2009.

22 Fukushima, et al., “User-oriented 3-D Display,” Journal of Information Processing, 47(4), 368–373, 2006.

(Accepted Sept. 9, 2010)



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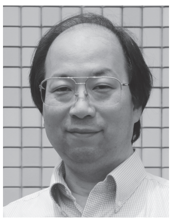

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