RePro3D: Full-parallax 3D Display with Haptic Feedback using Retro-reflective Projection Technology

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Abstract

We propose a novel full-parallax three-dimensional (3D) display system-RePro3D-that is suitable for interactive 3D applications with haptic feedback.Our approach is based on the retro-reflective projection technology in which several images projected from a projector array are displayed on a retro-reflective screen. When viewers view the screen through a half mirror, they see, without the aid of glasses, a 3D image superimposed in real space. RePro3D has a sensor function that recognizes user input; therefore, it can support some interactive features such as manipulation of 3D objects. In addition, a wearable haptic device, which is a part of our system, provides the user with a sensation of having touched the 3D image. In this paper, we describe the optical system of the high-density projector array used in RePro3D. Then, we describe the development of a prototype of RePro3D. The prototype is used to demonstrate that our system displays full-parallax images superimposed in real space from 42 different viewpoints. The proposed system enables a user to physically interact with the 3D image with haptic feedback.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 Introduction

When virtual objects are projected in three dimensions, viewers might get the feeling that the objects actually exist; these objects can also be manipulated such that they behave as though they are being physically touched. The scenario described in the preceding sentence has been depicted in science-fiction movies. It is expected that the use of stereoscopic displays in conjunction with user interface technologies will facilitate the realization of the abovementioned scenario.

In recent years, people have been enjoying three-dimensional (3D) images not only in movie theaters or amusement parks but also at their homes. Most existing stereoscopic displays are based on the concept of binocular stereo. A binocular-stereo-based display cannot render an accurate image with motion parallax and cannot create images that would provide different perspectives of the same image from multiple points of view. Motion parallax is considered to play a very important role in the manner in which humans perceive 3D shapes. In order to simultaneously display more natural stereoscopic images to a large number of people, multiview displays that provide different perspectives according to viewing directions are required. In addition, for a user to be able to view the displayed object as a real object, the displayed image should be superimposed not on a screen but in real space.

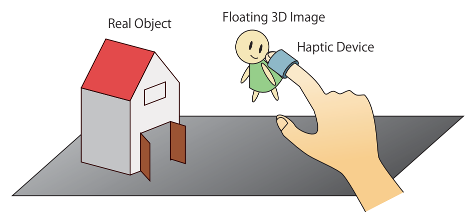

Figure 1: Concept of RePro3D. A floating 3D image is projected in real space. Users can touch the image directly.

Considerable research has been conducted on the development of user interfaces for interacting with 3D images. Multitouch technologies and vision-based gesture recognition are used to obtain inputs generated by the user's hand movements. Haptic displays produce a tactile sensation when the user touches virtual objects. The abovementioned technologies enable the users to interact with a 3D image by means of intuitive movements. However, a system that reproduces the sensation produced when directly touching an object has not yet been developed. One of the reasons is that the position of the user's hand is in different position of the displayed object. In order to provide some degree of haptic feedback to the user's hand, a haptic device should either be incorporated into the display or attached to the user's hand. Most stereoscopic display screens have a two-dimensional (2D) flat surface; however, for haptic interaction, users move their hands in 3D space. Thus, it is difficult to combine a stereoscopic display and a haptic interface.

Therefore, the purpose of our study is to achieve the following objectives:

1. generate autostereoscopic 3D images

2. superimpose 3D images in real space

3. develop a direct-touch interface for interacting with 3D images

To this end, we propose a novel full-parallax 3D display system RePro3D that is suitable for interactive 3D applications with haptic feedback. Figure1 shows the concept of RePro3D. For example, it will be possible for a CG character to appear from a real dollhouse and for a user to physically interact with the character with haptic feedback.

RePro3D is based on the retro-reflective projection technology (RPT). RPT has been researched to facilitate its use in developing visual display methods in augmented reality applications. In

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the conventional RPT method, an image is projected onto a retro-reflective screen by a projector to superimpose a virtual image in real space. In the proposed method, we use a high-density projector array in place of a single projector. A number of images from the projector array are projected onto the retro-reflective screen. Our method can generate vertical and horizontal motion parallax. When a user looks at the screen through a half mirror, he or she, without the use of glasses, can view a 3D image that has motion parallax.

We can choose from two types of projection methods for superimposing 3D images in real space. We have named the two methods as the real object projection method and the floating image method. In the real object projection method, we can choose a screen shape depending on the application. Image correction according to the screen shape is not required. Therefore, we can design a touch-sensitive soft screen, a curved screen , or a screen with an automatically moving surface. In the floating image method, the user can directly touch the 3D image by wearing a haptic device on his/her hand.

In this paper, first, we describe the principle of RePro3D. Then, we describe the implementation of the high-resolution optical system and the prototype device. Finally, we present a few results related to 3D projection and discuss the effectiveness of the proposed method.

2 Related Works

A number of studies on multiview 3D displays have been conducted in the past. Multiview 3D displays are generally based on either the integral imaging method[2, 3, 4] or the parallax barrier method[5]. In the integral imaging method, a lightfield is reproduced by placing an array of microlenses in front of the image. In the parallax barrier method, a barrier with a number of slits is placed in front of the image such that a different pixel is seen from different viewing angles. Although our approach is somewhat similar to the integral imaging method, it differs from both the methods mentioned above. In the integral imaging method, the resolution of an image from a viewpoint depends on the size of lenses. Therefore, it is difficult to improve the image resolution. In the parallax barrier method, it is difficult to generate vertical parallax. On the other hand, in our approach, the resolution of the image from a viewpoint depends on the projector resolution. Therefore, it is easy to improve the image resolution. In addition, our method can generate vertical and horizontal parallax. Further, the existing methods display a 3D image on a flat screen, and cannot superimpose the image in real space. Our method can be used to project a floating 3D image in real space, and users can view the projected image without the use of glasses.

Some projection-type display methods that superimpose images in real space by using projectors have been proposed[6, 7, 8]. The devices based on these methods project images on nonplanar, real surfaces that users can actually touch, thereby allowing the users to interact with the projected objects. However, such projected images are 2D in nature and multiview parallax images cannot be generated. In this study, we aim to create a projection-type full-parallax 3D display system.

3 Method

3.1 High-density Projector Array

Figure2 shows the basic principle of the proposed RPT-based 3D display method. When images from a projector array are projected onto a retro-reflector, there is a strong reflection of light in the direction of each projection lens. An identical number of viewpoints are created on either side of the axis of symmetry of the half mirror. When a large number of projectors are arranged in a matrix, a 3D image can be seen from multiple viewpoints.

In order to realize smooth motion parallax, the density of projectors in the projector array must be sufficiently high. However, with commercially available projectors, it is difficult to form a projector array that has projectors located very close to each other. One of the reasons for this is that the distance between adjacent viewpoints is limited by the size of each projector. In addition, the system scale would increase, and because of the large number of video outputs, system cost would also increase. Therefore, we have developed a high-density projector array by arranging a number of projection lenses in a matrix on a high-luminance LCD. The distance between viewpoints depends on the size of the projection lens. A single video output is produced, and the cost involved is lower than the cost of using many individual projectors. Figure3 shows the optical system of the high-density projector array. The system consists of a number of lenses, an LCD, a half mirror, and a retro-reflector that acts as the screen. The lenses are located at an appropriate distance from the image area of the LCD so that the projected areas of the projection lenses overlap. Shield plates are placed between the lenses to prevent light from other viewpoints from entering a lens. Figure3 shows the lateral view of the optical system; the overhead view would be identical to the lateral view.

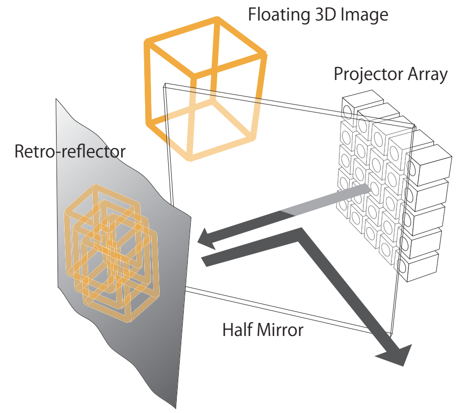

Figure 2: Basic principle of 3D display consisting of a projector array and a retro-reflector.

The luminance of the projected image depends on the LCD luminance, viewing angle, and retro-reflector performance. Even if the luminance of the projected image under normal illumination is so low that the image is not visible, it can still be seen at the focal points . The resolution of the image from each viewpoint depends on the LCD resolution. The number of viewpoints is equal to the number of projection lenses. This relationship between the resolution and the number of viewpoints is contrary to that in the integral photography method. RePro3D can generate vertical and horizontal motion parallax; however, the user must be positioned at a particular distance in the front-back direction .

3.2 Optical Design

Hereafter, we call the optical system of the projector array shown in Figure3 as "the basic system." The following expressions hold true for the basic system.

$$\frac{1}{a_0} + \frac{1}{b_0} = \frac{1}{f_0} \tag{1}$$

$$\frac{b_0}{a_0} = \frac{h_0}{l} \tag{2}$$

$$\frac{b_0}{a_0 + b_0} = \frac{d_0}{l} \tag{3}$$

where a_0 is the distance between the LCD and the projection lenses. b_0 is the distance between the actual image and the projection lenses. l is the length of each image shown on the LCD. h_0 is the

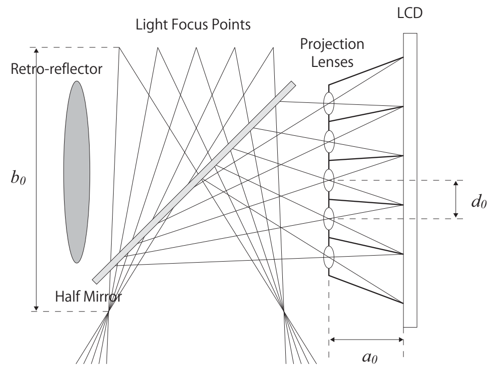

Figure 3: Optical system of the high-density projector array.

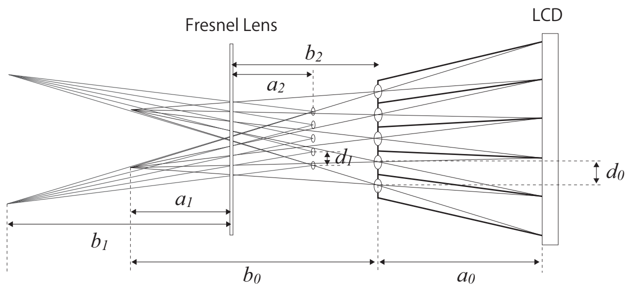

Figure 4: High-resolution optical system consisting of Fresnel lens.

size of the actual image shown on the LCD. f_0 is the focal length of the projection lenses. d_0 is the distance between adjacent projection lenses . On the basis of these expressions, we can determine the positions and specifications of the lenses to be used in the system .

The smoothness of motion parallax depends on the distance between adjacent projection lenses, d_0. In order to increase the number of viewpoints, d_0 should be minimized. However, if d_0 is too small, crosstalk will occur. On the other hand, if d_0 is too large, the luminance of different images will be discrete. In either case , viewers would see an unnatural image when they move their head. Therefore, we should determine the optimal distance.

b_0 and h_0 are parameters that depend on an application. b_0 corresponds to the distance between the user's eye and the screen on which the 3D image is projected; h_0 is the size of the projectable area. These parameters should be purpose-designed.

3.3 High Resolution Optical System using Fresnel Lens

In the basic system, there is a trade-off between the resolution and the size of the projected area. Thus, it is difficult to design an optical system that has a high resolution. To solve this problem, we develop a novel optical system with higher resolution and a larger projected area using a Fresnel concave lens. We call the novel optical system "the improved system." Figure4 shows the improved system.

A number of images of the content displayed on the LCD are gathered by the projection lenses. The gathered images are projected onto the screen using the Fresnel concave lens. The position of the focal points is the same as the position of the virtual image generated by a projection lens. Therefore, the distance between viewpoints is reduced optically. The following expressions hold true for the improved system.

$$-\frac{1}{a_1}+\frac{1}{b_1}=\frac{1}{f_1} \tag{4}$$

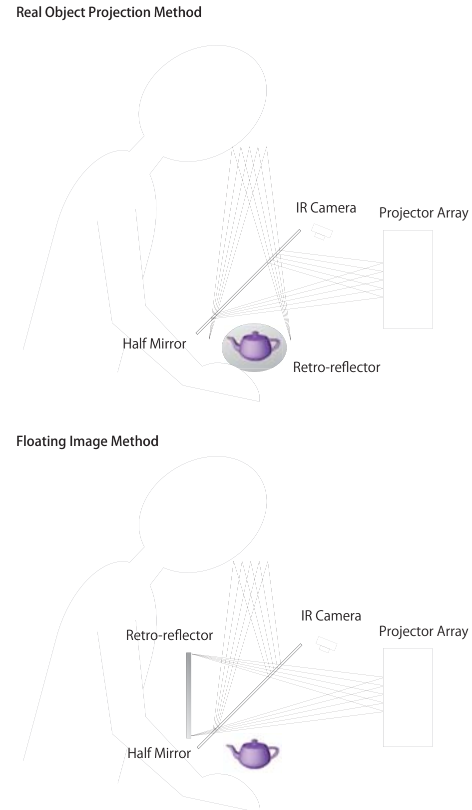

Figure 5: Two projection methods for superimposing 3D images in real space and IR-camera-based input interface.

$$\frac{b_1}{a_1}=\frac{h_1}{h_0} \tag{5}$$

$$\frac{1}{a_2}-\frac{1}{b_2}=\frac{1}{f_1} \tag{6}$$

$$\frac{b_2}{a_2}=\frac{d_1}{d_0} \tag{7}$$

$$a_1+b_2=b_0 \tag{8}$$

a_1 is the distance between the position of image of LCD produced by the projection lens and the Fresnel lens. b_1 is the distance between the position of image of LCD produced by the Fresnel lens and the Fresnel lens. a_2 is the distance between the projection lens and the Fresnel lens. b_2 is the distance between the focal points and the Fresnel lens. f_1 is the focal length of the Fresnel lens. h_1 is the size of the actual image of the content on the LCD. d_1 is the distance between the viewpoints. When the lenses are arranged such that they satisfy the above expressions, the high-resolution optical system can be achieved.

3.4 Projection Methods

As mentioned previously, to superimpose 3D images in real space, we can choose from two projection methods. Figure5 shows the two methods.

In the real object projection method, the retro-reflective screen is attached to a real object. Then, the image is projected onto the object. The screen shape can be selected depending on the application requirements. Image correction according to the screen shape is not required. Therefore, we can design a touch-sensitive soft screen, a

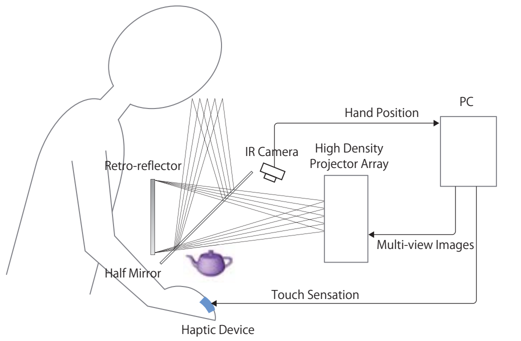

Figure 6: System overview.

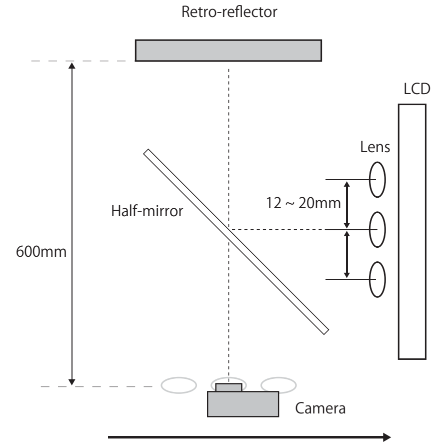

Figure 7: Experimental condition.

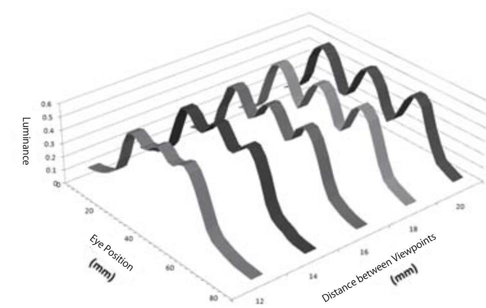

Figure 8: Luminance value as a function of spacing between projection lenses.

complexly curved screen, or a screen with an automatically moving surface.

In the floating image method, the retro-reflective screen is arranged as shown in Figure5 and the user cannot see the screen directly. The projected image seems to float in the air when it is seen through a half mirror. The user can directly touch the 3D image by wearing a haptic device on his/her hand. This method is suitable for some applications in which the image is required to move around autonomously.

3.5 Input Interface with Haptic Feedback

RePro3D has an intuitive input interface that recognizes the movement of the user's hand by means of an infrared camera. The camera is located in the projected area, as shown in Figure6, and it captures images of the user's hand movements. Upon the detection of contact between the user's hand and the projected image from the captured image, the system recognizes the degree of contact . According to the recognition result, image position and image posture are updated.

In addition, the user wears a haptic device on his/her finger. When the user touches the 3D image, he/she feels a tactile sensation generated by the haptic device. The mechanism that produces the sensation on a user's finger is based on a technology called Gravity Grabber[9]. Gravity Grabber produces fingerpad deformation using a pair of small motors and a belt. To create a "push" sensation, the dual motors are driven in opposite directions so that they roll up the belt, thus delivering a vertical stress to the user's fingerpad. The belt tension is determined by the degree of contact between the finger and the 3D image.

4 Results

4.1 Optimization of the Distance between Viewpoints

As mentioned in Section 3.2, we should determine the optimal distance that results in less crosstalk and smooth motion parallax. We performed an experiment to determine this distance.

Figure7 shows the experimental setup. We arranged an LCD, a half mirror, a retro-reflective screen (Reflite, 8301), and three projection lenses as shown in Figure7. The distance between the viewpoints and the screen was 600 mm. The projection lenses were 12 mm in diameter, and their focal length was 48 mm. A white square was displayed on the LCD, and the size of the square on the retro-reflective screen was 100 mm$\times$100 mm. The luminance of the LCD was 400 cd/m^2.

We placed a digital camera on the straight line on which the focal points lie. This camera was used to capture the image of the white square projected on the retro-reflective screen. The distance between the projection lenses was varied from 12 mm to 20 mm. We calculated the average luminance of the pixels in the white square for each picture. Figure8 shows the relation between the luminance value and the spacing between viewpoints.

From this figure, it can be seen that the change in luminance is directly proportional to the distance between the viewpoints. When the distance between the viewpoints is in the 12-16 mm range, the change in luminance is less than 20%.

4.2 Optical Simulation and Implementation

In the improved system, it is difficult to directly calculate the optical parameters that satisfy the relational expressions of the system. In addition, we should consider the specifications of available equipment, such as the size of a lens or the resolution of an LCD. Therefore, we wrote an optical simulation program that determines the optimal parameters (Figure9). We used this simulator to determine the optical parameters, which are listed in Table1.

On the basis of the simulation results, we built a prototype of the system. Figure10 shows the prototype. We used 42 projection lenses, each of diameter 25 mm and focal length 25 mm. The Fresnel concave lens used in the prototype was 370 mm in diameter and its focal length was -231 mm. We used a high-luminance LCD with a resolution of resolution 1680$\times$1050 pixels and luminance of 1000 cd/m^2. The floating image method was selected as the method of projection.

The projection lenses were arranged in a 6 (rows) $\times$ 7 (columns) matrix; therefore the total number of viewpoints was 42. The resolution of the projected image seen from each viewpoint was 175$\times$175 pixels. The device could project up to a distance of 400

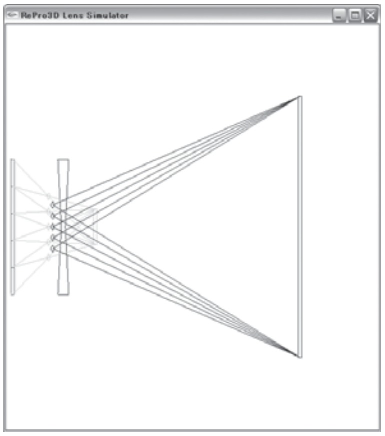

Figure 9: Optical simulation software.

Table 1: Optical parameters of the prototype device.

f_0	125 mm
a_0	209 mm
b_0	310 mm
d_0	30 mm
f_1	-231 mm
a_1	128 mm
b_1	284 mm
a_2	182 mm
b_2	101 mm
d_1	16 mm

mm from the user's viewpoint. The image was projected in a space of size 200 $\times$ 200 $\times$ 300 mm.

Figure11 shows the 3D object that was projected onto the retro-reflective screen and can be seen from several viewpoints. The positional relationship of each displayed objects changes according to the change of viewpoint. This finding shows that our proposed method can produce a stereoscopic image superimposed in real space with smooth motion parallax.

4.3 Interaction with 3D Image

We placed an infrared camera (Point Gray Research, Firefly MV) with an IR pass filter and infrared LEDs above the projected area to capture the user's hand movements. Then, we implemented the user input system, which recognizes the degree of contact between the user's hand and the displayed image. Using this function, we built an application that enables the user to touch a character floating in space. If the user touches the character, the character reacts to the user's touch and the user can perceive this reaction by looking at the changes in the character's appearance and sound cues. Figure12 shows the application; the character, an animated fairy, floating in real space, reacts upon being touched by the user's finger.

Thereafter, we implemented the haptic feedback system. Figure13 shows the result of image processing . The belt tension is determined by the degree of contact between the finger and the 3D image. Figure14 shows the user's finger with the haptic device on it.

5 Discussion

RePro3D can generate a 3D image that is superimposed in real space with smooth motion parallax. However, from a particular

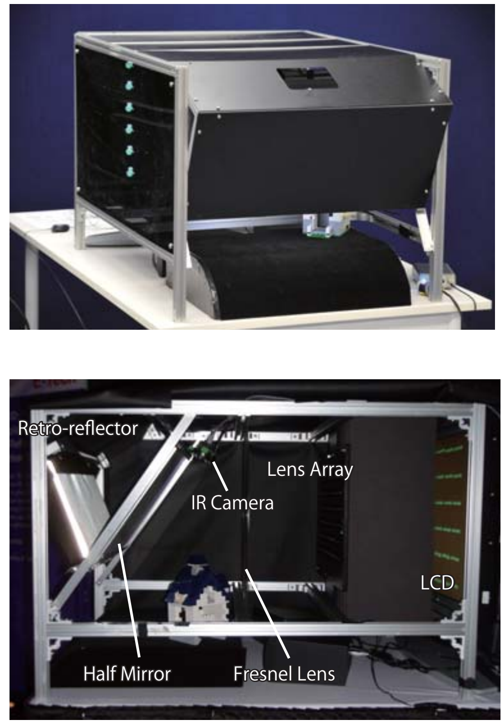

Figure 10: Prototype of the system.

viewpoint, some level of blur and crosstalk could be seen in the image. At first, we discuss the cause of the blur. When the viewpoint moves, the image edges appear blurry; however, the blur cannot be seen in the center of the image. One of the reasons to which this blur can be attributed to is the effect of the angle of incidence of light rays on the Fresnel concave lens. The angle of incidence increases as we move from the center of the image toward its edges. In order to decrease such blurring, we should choose a lens that is robust to changes in the angle of incidence.

Next, we discuss the cause of crosstalk. When a viewpoint moves back and forth, there are a few points on this path of motion from which several different images can be seen. This problem is attributed to the retro-reflector performance. The retro-reflector strongly reflects the light in the incident direction; however, there is a minor diffuse component. Therefore, at a viewpoint that is located far away from the focal points, several images will appear to be merged. In Section 4.1, we obtained the optimal distance between the viewpoints along the vertical and the horizontal directions. In order to increase the area in which the user can see a more natural 3D image, we should optimize the optical parameters by taking into consideration the crosstalk that results from the back-and-forth motion of the viewpoint.

Finally, we discuss the result of the interaction between the 3D image and the user's hand. Users can intuitively interact with the virtual character floating in real space. When the user places his/her hand into the projected area, the stereoscopic sensation does not disappear. This finding implies that the 3D image is naturally superimposed in real space. However, when the user places his/her hand in front of the displayed object, the object was not hidden by the user's hand; this is a shortcoming of the system . As future work, we intend to measure the shape and depth of a user's hand and display the correct positional relationship between the hand and the displayed object .

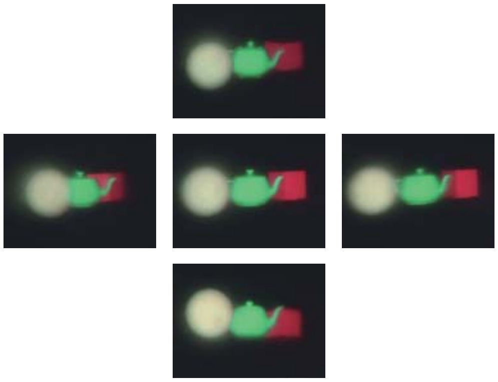

Figure 11: Projection of 3D object onto the retro-reflective screen as seen from multiple viewpoints.

Figure 12: Interaction between user's hand and 3D image.

6 Conclusion

In this paper, we propose a novel full-parallax 3D display system RePro3D that is suitable for interactive 3D applications with haptic feedback. We designed an optical system consisting of a high-density projector array; we built the projector array using an LCD and a number of projection lenses. Then, we used a Fresnel concave lens to improve the resolution of the designed system. Next, we performed an experiment and an optical simulation to obtain the optimal parameters of the optical system. On the basis of the results of the experiment and the simulation, we built a prototype of the system that could produce 42 parallax images. The prototype showed that our proposed method can produce stereoscopic images superimposed in real space with smooth motion parallax. Finally, we created a user interface that enables users to physically interact with a virtual character floating in space. As a result, using RePro3D, we created a visual and haptic interface that enables users to see and touch a virtual 3D object as if the object were real.

Acknowledgements

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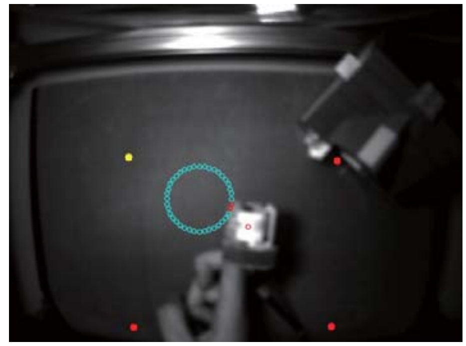

Figure 13: Result of image processing for detecting contact between the 3D image and the user's hand.

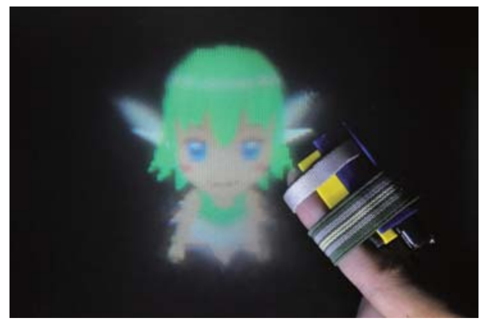

Figure 14: User touching the floating 3D character. Haptic feedback is provided to the user by the wearable haptic device.

References

[1] M. Inami, N. Kawakami, D. Sekiguchi, Y. Yanagida, T. Maeda and S. Tachi: Visuo-Haptic Display using Head-Mounted Projector, Proceedings of IEEE Virtual Reality 2000, pp.233–240, Mar 2000

[2] G. Lippmann: La photographie integrale, Comptes-Rendus 146, pp. 446.451, 1908

[3] Roberto Lopez-Gulliver, Shunsuke Yoshida, Sumio Yano, Naomi Inoue: gCubik : Real-time Integral Image Rendering for a Cubic 3D Display, ACM SIGGRAPH 2009 Emerging Technologies, New Orleans, USA, August 3-7 2009

[4] Koike, T., Sakai, H., Shibahara, T., Oikawa, M., Yamasaki, M., and Utsugi, K. :Light field copy machine. In ACM SIGGRAPH ASIA 2009 Emerging Technologies: Adaptation (Yokohama, Japan, December 16 - 19, 2009). SIGGRAPH ASIA '09.

[5] Sakamoto, K.; Kimura, R.; Takaki, M.: Parallax polarizer barrier stereoscopic 3D display systems, Active Media Technology, 2005. (AMT 2005). Proceedings of the 2005 International Conference on , pp.469- 474, 19-21 May 2005

[6] Daisuke Kondo, Toshiyuki Goto, Makoto Kouno, Ryugo Kijima and Yuzo Takahashi: A Virtual Anatomical Torso for Medical Education using Free From Image Projection, Proc. of the 10th International Conference on Virtual Systems and Multimedia, pp678-685, 2004

[7] A. Cassinelli and M. Ishikawa: Khronos projector. In SIGGRAPH 2005, Emerging Technologies, 2005.

[8] Y. Kawaguchi:The Art of Gemotion in Space, Information Visualization, 2006. IV 2006. Tenth International Conference on , vol., no., pp.658-663, 5-7 July 2006

[9] Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami and Susumu Tachi: Gravity Grabber: Wearable Haptic Display to present Virtual Mass Sensation, 34th Int. Conf. On Computer Graphics and Interactive Techniques (ACM SIGGRAPH 2007), Emerging Technologies, 2007.