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Immersive Augmented Reality Display System Using a Large Semi-transparent Mirror

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Abstract

This paper proposes an immersive augmented reality display system, named "AR View", that generates a high presence augmented reality environment using the immersive projection technology. In this system, the stereoscopic image of virtual objects, projected onto a floor screen by stereo projectors and real objects placed in front of, or behind, a highly transparent mirror film are combined optically, using the mirror, placed at an angle of 45 degrees to the floor. In order to create correct occlusion effect in over large area of the augmented realty environment, light projectors have been used to illuminate the surface of real objects using the occlusion shadow function, rather than standard light bulbs. The AR View was applied to various applications such as the high presence communication using a video avatar, by connecting it to a broadband network.

Categories and Subject Descriptors (according to ACM CCS): I.3.1 [Computer Graphics]: Three-dimensional displays

1. Introduction

Recently, the use of augmented reality (AR) technology has become very popular, and has been applied to various application fields, such as entertainment [TCD*00] and medicine [MFO92]. Currently, optical see-through or video see-through head-mounted displays are mainly used for the AR displays [Azu97]. However, see-through head-mounted displays have several problems or limitations. For example, the user must wear a heavy device, and he often sees a scene with a positional gap between the real and virtual objects, due to the time delay as he turns his head quickly [Hol97].

On the other hand, immersive projection displays, such as the CAVE [CNSD93]or CABIN [HOIY99], are often used in the field of virtual reality (VR). Although the user in immersive projection displays does not need to wear a heavy device and experiences the virtual world with little time delay, these displays can not be directly applied to the AR system because the large screens mask the real environment around the user. This research aims at constructing a high presence AR environment by using an immersive projection technology.

Several projection based AR systems that use a transparent screen, the physical objects' surfaces or a semi-transparent mirror have already been proposed. Invisible Interface [OYYH01] uses a transparent HoloPro glass screen for the projection of stereo images, but the transparency of the glass screen is not particularly high and the viewing angle is limited, because the permeating light is directional. Shader Lamps [RWLB01] projects the virtual scene onto three-dimensional physical objects and the user can observe the scene from various directions. But the displayed image has restrictions due to the size, shape, and color of the surface of the physical object. Extended Virtual Table [BEB01] and Virtual Showcase [OFSE01] consist of a horizontal projection screen and half-silvered mirror. In these systems, the virtual image and the real objects can be seen, optically integrated in the same space, but the users can experience little immersion because the display space is constructed on a desktop.

In this research, we propose the immersive augmented reality display system, named "AR View", that uses large semi-mirrored film with high transparency. This system optically combines the virtual scene with the real environment, both in front of, and behind, the semi-mirrored film so that the user can experience an immersive augmented reality environment with a wide field of view. Because the large semi-mirrored film is used to display virtual objects, user's viewing angle is not limited and displayed image is flexible for size and shape. In addition, the virtual world and the real world can be integrated three dimensionally, since the stereoscopic image of the virtual objects can be displayed. But users do not need to wear a heavier device than HMDs. In general, an AR system using the semi-transparent mirror has the problem of occlusion between virtual and real objects. To address this problem, we used light projector technology. This method of creating the correct occlusion effect by using the light projectors was proposed by Bimber et al. for their desktop applications [BF02]. AR View generates the correct occlusion effect over a wide area of the immersive augmented reality environment.

2. The Structural System of AR View

2.1. System Configuration

Figure 1 shows the system appearance and figure 2 shows the structure of AR View. In this system, a semi-mirrored film

Figure 1: *Photograph of 'AR View' equipment.*

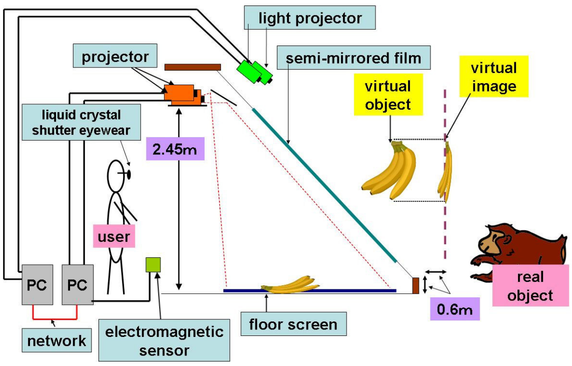

Figure 2: *Structure of 'AR View' system.*

was placed at an angle of 45 degrees to the floor. Two stereo projectors were placed, side by side, at the top of the semi-mirroed film, with the stereo images being projected through the mirrors in front of the projectors. The images were projected onto the floor screen, along the semi-mirrored film, so as not to cast the shadows of the users. Thus, the users could see the virtual image that is reflected by the mirror film in front of them. Since the transparency of the semi-mirrored film was high (visible light transmission is 87.8 %), the users could observe the real world behind the mirror as well as the real world in front of it.

In this system, InFocus DepthQ DLP projectors were used to project active stereo images of virtual objects. The left eye and right eye images were projected, alternately, at 100Hz, so that the user could see the stereo image of the virtual objects by wearing StereoGraphics CrystalEyes3 liquid crystal shutter eyewear that was synchronized with the refresh rate of the graphics output. In addition, since an electromagnetic sensor, Polhemus FASTRAK, was attached to the shutter glasses to track the user's viewpoint, the stereoscopic images, seen from the user's viewpoint, could be generated in real time.

Two PC are used for AR View. One of them is used for the electromagnetic sensor and two stereo projectors, and another is used for light projectors shown in chapter 3 in detail (see figure 2). To synchronize the images by stereo projectors with the images by light projectors, the PC for the electromagnetic sensor sends the data from the sensor to the PC for light projectors through network by UDP. Thus, the scene, made up of virtual objects was combined with the real environment in three-dimensional space.

2.2. User's Field of View

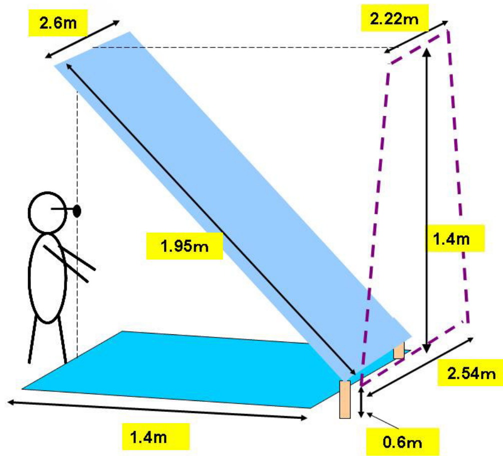

Figure 3: *Overall image size.*

The user sees the images projected on the floor screen at the position of the vertical virtual image plane, which is positioned symmetrically with respect to the semi-mirrored film.

Since the semi-mirrored film is located 0.6m above the floor so that the user cannot see the floor screen at the same time, the virtual image plane is positioned 0.6m behind the bottom edge of the semi-mirrored film and 0.6m above the floor.

The size of the semi-mirrored film is 2.60m wide and 1.95m high. Since the keystone distortion of the projected image is corrected by the software, the shape of the projected image is an isosceles trapezium. The length of the image projected on the floor screen by one projector is 1.40m, and the width of the nearest edge and the farthest edge are 1.52m and 1.87m,respectively. In this system, two projectors were used to generate images with a wide field of view, and the projected images are blended by overlapping sections of the images with edge blending. The height of the total image projected by the two projectors is 1.40m, and the width of the upper edge and the lower edge are 2.22m and 2.54m, respectively (cf. figure 3).

The field of view of the displayed image on the virtual image plane depends on the position of the user's viewpoint. When the user's viewpoint is located at the depth of the near edge of the floor screen and at the center of the width and height of virtual image plane (cf. figure 3), the horizontal and vertical fields of view, θ_H and θ_V ,covered by the virtual image plane, are represented as follows (see figure 4):

$$\theta_H = \frac{180}{\pi} \cdot 2\arctan\frac{1.19}{1.4+0.6} \fallingdotseq 61.51(degrees)$$

$$\theta_V = \frac{180}{\pi} \cdot 2\arctan\frac{0.7}{1.4+0.6} \fallingdotseq 38.58(degrees)$$

These are satisfactorily greater than the central visual field

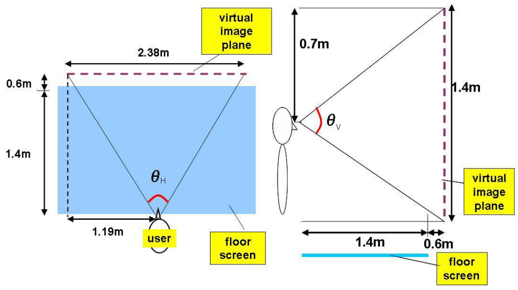

Figure 4: *User's horizontal and vertical fields of view in the image plane.*

of the viewer. These are the reason why user feels immersed in the virtual environment for field of view [CR06].

3. Light Projector

3.1. The Purpose and Outline of the Light Projector

In this system, since the virtual image is displayed reflected by the semi-mirrored film, the representation of correct occlusion effect between virtual objects and real objects is difficult when the virtual object is displayed, overlapped by the real one, as shown in figure 5 left. In this case, the user may perceive the real object that is located behind the virtual object, because the luminance of the virtual image is not as high, compared with the luminance of the real object. However, when the light that illuminates the real object is extinguished, the user might not perceive the existence of the real object. In AR View, light projectors were used, instead of the standard light bulbs, to generate the correct occlusion effect between virtual and real objects. Using this method, the shapes and the positions of the real objects behind the mirror are measured beforehand, and the light projector illuminates the real objects using the computer-controlled light intensity.

When the real object is located in front of the virtual object, the whole area of the real object is illuminated by the light projector using the white light and the part of the virtual object's image that is overlapped by the real object is blackened to create the occlusion effect. On the other hand, when the virtual object is located in front of the real object, the occlusion shadow is created on the real objects' surface where the real object is occluded by the virtual object. In the area of the occlusion shadow, the luminance of the virtual image that overlaps the real object is made brighter than the real object. Thus, the light projectors are effectively used to generate the correct occlusion effect between the real object and the virtual object as shown in figure 5 center and right. In this research, two LED projectors, TOSHIBA TDPFF1A,

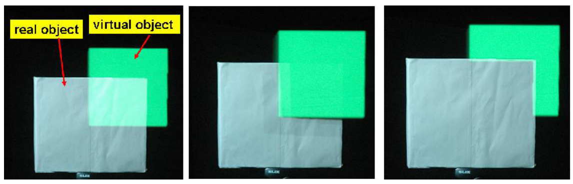

Figure 5: *Use of the light projector.*

were sited at the upper edge of the semi-mirrored film and they are used as light projectors. Since the brightness of the LED projector is low (15 ANSI lumens), it can be used to illuminate a human who is standing behind the semi-mirrored film, as well as the real objects.

3.2. Process of Generating Occlusion Shadows

The illumination image for the occlusion shadows that is projected onto the real objects' surface is generated using a shadow mapping algorithm as follows. In this process, the illumination image seen from the user's left eye position was generated, because the light projectors do not have a stereo function.

(1) The user's left eye position is measured by the electromagnetic sensor and the perspective projection image of the virtual objects, seen from the user's left eye position, is rendered and it is saved in the depth texture.

(2) The 3D model of the real objects with white color, whose shape and the position were measured beforehand, is created and the depth texture is mapped onto it using the projective mapping from the user's left eye position. In this case, the black color is mapped to the pixels whose depth value is greater than the corresponding value in the depth texture.

(3) The image of the real objects on which the depth texture was mapped is rendered, seen from the position of the light projector using the perspective projection, and it is projected by the light projector as the illumination image.

In addition, the 3D models of the real objects with black color are rendered with the virtual objects and they are projected as the virtual image, in order to represent the black part of the virtual objects, overlapped by the real objects.

Thus, the augmented reality scene with the correct occlusion between the virtual objects and the real objects is generated as shown in figure 5 center and right.

4. Evaluation of Light Projector

Next, we conducted an experiment to evaluate the function of the light projector representing the occlusion effect. The accuracy of the user's depth perception was compared, with and without the use of the occlusion shadow from the light projector.

4.1. Experimental Method

In this experiment, a universal coordinate system which is common to the virtual world and the real world is used, as shown in figure 6. The x-axis is defined as parallel to the virtual image plane and the floor, y-axis is vertical to the virtual image plane and z-axis is vertical to the floor. The origin of x-coordinate is defined at the midpoint of the width of floor screen, and the origin of y-coordinate is 1.0m in front of the virtual image plane, while that of z-coordinate is at the floor. The subject sat on the chair while wearing the liquid crystal shutter eyewear. The chair was placed in front of the semi-mirrored film in the position (0.0, -2.1, 0.0). The real object, consisting of white box with a size of 0.31 × 0.09 × 0.26m , was placed behind the mirror film in the position (0.0, 1.15, 1.25), and a virtual object of the cubic box was displayed as the virtual image.

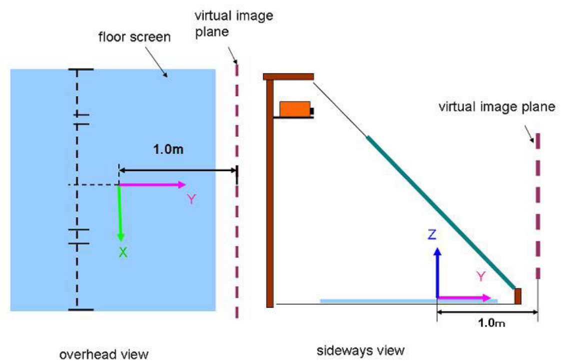

Figure 6: *Co-ordinate system used.*

The virtual cubic box was located at the various depths positions, with y-coordinates of 1.8, 1.4, 1.0, 0.6, 0.2, -0.2 -0.6, and -0.8, so that the part of real box was overlapped by the virtual box when they were seen from the subject's viewpoint, as shown in figure 7. In this case, since the image of the virtual box was rendered using the perspective projection, the box located near the subject was drawn larger than the box located farther from him on the virtual image plane. Therefore, the size of the virtual box was changed in proportion to the distance from the subject's left view position so as to make the appearance of size constant. The virtual box was

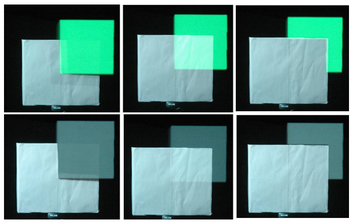

Figure 7: *The examples of the displayed images.*

displayed in one of the eight positions, with the real box in two different condition, where the function of the occlusion shadow was either used or not. Namely, sixteen scenes were given randomly to the subject, and he was asked to answer the question "Is the virtual box located in front of the real box or behind the real box?" with the options 'in front of the real box', 'behind the real box' and 'no idea'. The experiment was conducted using four different color conditions for the virtual box that included 'bright green', 'dark green', 'bright white' and 'dull white'. Five subjects each performed the experiment three times.

4.2. Result and Analysis

Figure 8 shows the results of this experiment. This graph indicates the correct answer rates in the cases where the light projectors were and were not used. This graph indicates that the correct answer rate increased when the light projectors were used. From the result, we can consider that the light projectors improved the users' depth perception in the augmented reality environment where real and virtual objects were integrated. In the graph displaying the use of the light projector, the correct answer rate was a little low when the virtual object was located close to the subject. The light projector used in this system cannot output a stereo image, synchronized with the virtual image, because the refresh rate of the LED based light projector is below 75Hz. For this

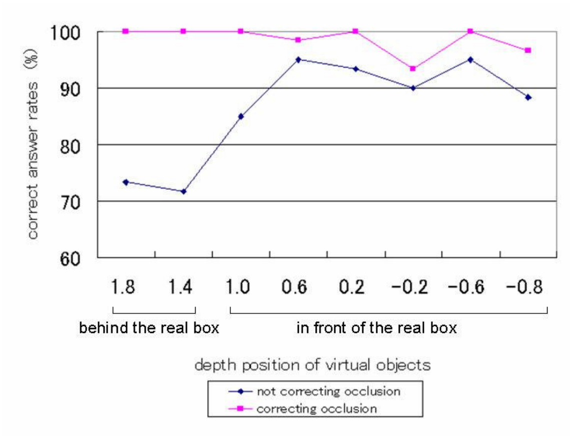

Figure 8: *Comparison of results, with and without occlusion correction of images.*

reason, the light projector creates only the shadow image occluded by the virtual object seen from the user's left eye position. Consequently, the larger the depth between the virtual objects and the real object, the larger the positional error between the shadow that is projected onto the real object's surface and the virtual object's image, seen from the right eye position, as shown in figure 9 left. This seems to be the reason for the decrease in the correct answer rate when the virtual object is located close to the subject. From the results of this experiment, we can conclude that the user can perceive the correct positional relationship between a real object and a virtual object when the distance between them is within 1.0m. Namely, the error between the shadow and the virtual object's image for the right eye, θ_d (deg) shown in figure 9 right, should be within 0.49 deg (we assume subjects' heads are at (0.0,-2.1,any) and user's veiwing direction is vertical to the virtual image plane). In this system, the low

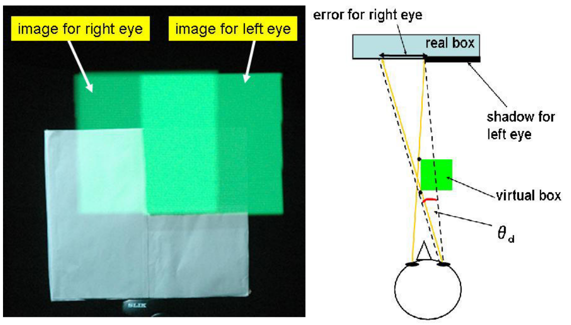

Figure 9: *Stereo parallax image and shadow projected onto the surface of real object.*

brightness LED projectors were used as the light projectors so that they could illuminate a human standing behind the semi-mirrored film. However, the above mentioned problem would be solved by using the light projectors that have a refresh rate of more than 100Hz and would synchronize with the projected stereo image of the virtual objects.

5. Applications of an Immersive Augmented Reality Environment

5.1. Augmented Reality Exhibition

The AR View can be applied to various augmented reality applications. First, it was applied to constructing an exhibition environment. Figure 10 shows an example in which a notebook computer is exhibited behind the semi-mirrored film in the real world, while a computer graphics character is represented as the virtual image. In this example, the computer graphics character behaved as an agent of the exhibitor to explain the exhibit. Since the mirrored film is very

Figure 10: *An example of the exhibition environment.*

transparent, the user can barely perceive the existence of the mirror and is able to experience the augmented reality environment over a wide field of view. Although the computer graphics character moved in an extended area, it could be seen in the three-dimensional location, with correct occlusion effect, by using the stereo image and the light projector function. For example, figure 10 left shows that the computer graphics character is standing in front of the notebook computer and figure 10 right shows that the character is standing behind it.

5.2. Application to Video Avatar Communication

The AR View can be applied, not only to stand-alone applications, but also to interactive communication with the remote users. In this study, AR View was connected to the JGN2 (Japan Gigabit Network 2) network and a communication environment was constructed using the video avatar. The video avatar is a technology which achieves a high presence communication by simultaneously transmitting a live video image of the user in a shared virtual world. In this system, the video avatar image of the remote user was integrated into the real environment, in which the local user was located, by simply projecting it as a virtual image. Since the mirror film in the AR View is very transparent, the video camera can be placed behind the mirror, in front of the user, and the user's image can be captured through mirror, from the front (see figure 11). Figure 12 shows the example of

Figure 11: *How to shoot the use's image.*

the video avatar communication experience using the AR View. These confirm the expectation that this system can effectively be used for teleconferencing or collaborative working with remote users, while sharing the augmented reality environment with highly realistic sensations.

Figure 12: *The example of how video avatar is used by AR View.*

6. Conclusions

In this research, an immersive augmented reality display system, named AR View, was developed to optically combine a virtual environment with a real environment, over a wide field of view, by using the highly transparent, large semi-mirrored film. In this system, light projectors were used to achieve the correct occlusion effect over an extended area of the immersive augmented reality environment. In addition, this system was applied to high-presence communication with a remote user by connecting it to the JGN2 network, as well as to stand-alone applications.

Future work will include the development of a light projector technology to dynamically generate the correct occlusion effect by measuring the shape and the movement of real objects in real-time. Additionally, we will create practical applications for AR View.

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