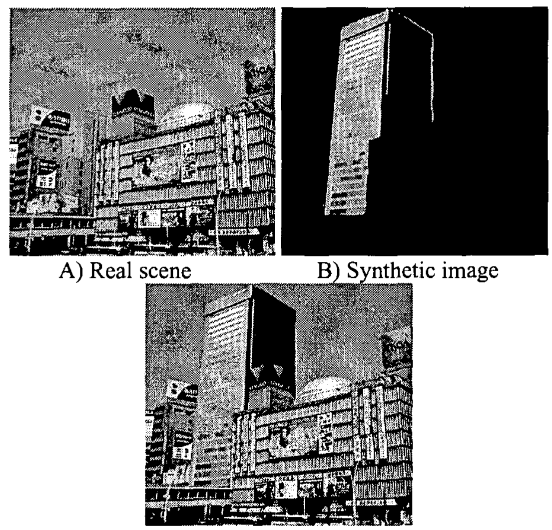
An Optical See-through Display for Mutual Occlusion of Real and Virtual Environments

Kiyoshi Kiyokawa*, Yoshinori Kurata**, Hiroyuki Ohno*
*Communications Research Laboratory (CRL)
4-2-1 Nukui-Kitamachi, Koganei, Tokyo, 184-8795, Japan
**Topcon Co.
75-1 Hasunuma-cho, Itabashi-ku, Tokyo, 174-8580, Japan
kiyo@crl.go.jp, y.kurata@topcon.co.jp, hohno@ohnolab.org

Abstract

In a mixed reality system, mutual occlusion of real and virtual environments enhances the user's feeling that virtual objects truly exist in the real world. However, conventional optical see-through displays cannot present mutual occlusion correctly since the synthetic objects always appear as semitransparent ghosts floating in front of the real scene. In this paper, we propose a novel display design that attacks this well-known unsettled problem. Our optical see-through display with mutual occlusion capability has following three advantages: 1) Since the light-blocking mechanism is embedded inside the display and no additional setting is needed, it can be used anywhere, e.g., outdoor, 2) Since incoming light can surely be cut off in any situation, virtual images keep their original intended colors, e.g., black, 3) Since the light-blocking mechanism is separated with the display for color graphics, most existing see-through displays can be employed. We also describe our prototype display that has confirmed the effectiveness of the approach.



A) Real scene B) Synthetic image C) Final result

Figure 1. An example of mutual occlusion.

Figure 2. An example of conventional image overlay of an optical see-through display.

1. Introduction

The goal of mixed reality technology is to realize environments that seamlessly integrate both real and virtual worlds [1]. In a mixed reality system, mutual occlusion of real and virtual objects enhances the user's feeling that virtual objects truly exist in the real world. This is an essential feature for some mixed reality applications, such as architectural previewing. Besides, in terms of cognitive psychology, incorrect occlusion confuses users [2]. Figure 1 shows an example of mutual occlusion. Figure 1(A) is a real scene that a synthetic image is superimposed onto. Figure 1(B) is the synthetic image. And figure 1(C) is the final result of image overlay.

To present mutual occlusion of real and virtual environments, depth information of a real scene and a display that can really show images of mutual occlusion are needed. Recently, depth information of a real scene can be acquired in real-time by stereo-paired cameras or laser range finders [3][4][5].

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On the other hand, see-through displays often used for mixed reality are classified into two types: video see-through and optical see-through [6]. Conventional optical see-through displays cannot present mutual occlusion correctly since the synthetic objects always appear as semitransparent ghosts floating in front of the real scene. Figure 2 illustrates an example of semitransparent image overlay of a typical optical see-through display. So, video see-through displays have been exclusively used when realizing mutual occlusion [3][7]. However, they degrade the real image in terms of low spatial and temporal resolution, limited depth-of-field, fixed-focus and so on.

We developed a novel optical see-through display that can present mutual occlusion of real and virtual environments, by using a transparent LCD panel [8]. In this paper, we propose the display's design and show a prototype display and experimental results. This paper is organized as follows: In Section 2, characteristics of two types of displays, video see-through and optical see-through are explained. Section 3 gives a brief survey of prior work. In Section 4, basic concepts and characteristics of our new optics design are described. Sections 5 and 6 describe a prototype display and its experimental usage. Finally, Section 7 gives conclusions and future work.

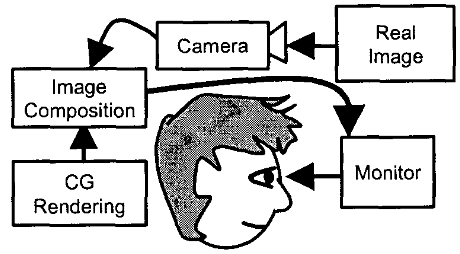


Figure 3. Video see-through display.

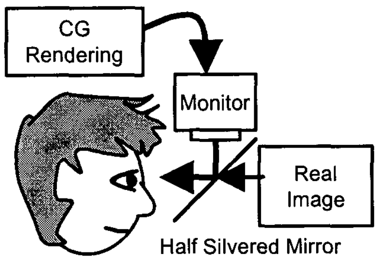


Figure 4. Optical see-through display.

2. Conventional Displays

2.1. Video see-through displays

Figure 3 shows a typical configuration of a video see-through display. With a video see-through display, a synthetic image is combined with a real image electronically that is captured by video cameras mounted on the display, and the combined image is presented in front of the user's eyes. Three advantages of video see-through displays are as follows.

1) Pixel-based image processing for a real scene, e.g., correction of intensity and tint, blending ratio control, is realized.
2) In each rendered frame, temporal registration error can be eliminated if a real image and a virtual one are synchronously processed and presented.
3) Implicit and explicit visual information laid in a real scene can be utilized. For example, depth information of a real scene can be calculated from multiple images [3], and relative orientation and translation between an environment and a user can be acquired by using visual features [7].

Owing to the first advantage, video see-through displays can handle the occlusion problem without difficulty. If the system knows depth information of a real scene, the system has only to choose one source out of two image planes, synthetic and captured ones, for each pixel to render a combined image with correct occlusion. Hence, this type of display has been used for realizing mutual occlusion so far. However, a video see-through display degrades rich information of the real world in terms of low spatial and temporal resolution, limited depth-of-field, fixed-focus and so on. Another demerit is that a user may lose his/her sight under a system trouble.

2.2. Optical see-through displays

Figure 4 shows a typical configuration of an optical see-through display. A typical optical see-through display allows a user to see the real world and a virtual environment simultaneously through a partially transmissive and reflective mirror. These types of displays have relatively simple structures and they are widely used. They preserve the real image as it is without any degradation. However, conventional optical see-through displays have a significant disadvantage. That is, the synthetic objects always appear as semitransparent ghosts floating in front of the real scene. Thus, influenced by color of the real image, each pixel of a synthetic image never shows its original color. Consequently, they cannot display mutual occlusion of the real and virtual environments correctly as shown in Figure 2.

Recently, however, researchers have made a few attempts to build new optical see-through displays that attack the occlusion problem. In the next section, we will describe the previous work and discuss their problems.

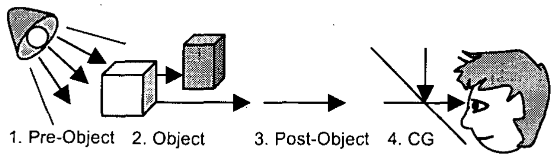


Figure 5. Ray paths of an optical see-through display.

3. Previous Work

3.1. Ray paths of an optical see-through display.

Before describing previous work, let's consider ray paths of an optical see-through display for better understanding and easy classification. To realize mutual occlusion with an optical see-through display, we have to cut off any rays of a real scene and let them go selectively based on the mask pattern. Figure 5 shows ray paths of an optical see-through display. 1) First, rays are emitted from a light source, 2) then they reflects on real objects, and 3) they go through the air, and 4) part of them are blended with synthetic images by an optical combiner such as a half mirror, and finally jump into user's eyes. Corresponding to these four portions in a path, four methods are conceivable to cover a real scene with a synthetic image:

[R1] Cut rays off between a light source and objects[4].
[R2] Cut rays off by locating special real objects[9][10].
[R3] Cut rays off between objects and user's eyes.
[R4] Decrease visibility of a real scene by increasing the intensity of a synthetic image.

On the other hand, corresponding to these four methods, following three methods are conceivable to cover a synthetic image with a real scene.

[V1,3] Omit rendering pixels that should disappear[4].
[V2] Locate screens behind the real objects[10].
[V4] Decrease visibility of a synthetic image by increasing the intensity of a real scene[9].

In the following, three approaches of previous work are described.

3.2. Approach 1: Intensity control.

Kameyama developed a CAD system that users virtually perceive mutual occlusion, by controlling the intensity of a real environment appropriately [9]. In the system, the user manipulates a black input device on which a synthetic image is superimposed through a half-silvered mirror (method [R2]). User's hands are so brightly lit that fingers in front of the device can be seen clearly. So the user perceives the fingers cover the synthetic image (method [V4]). Though this approach is relatively simple and effective, a real counterpart is needed for each virtual object, and light condition must be carefully controlled.

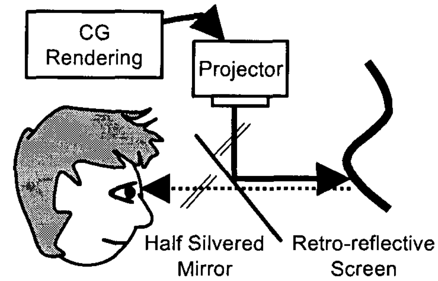


Figure 6. Head mounted projector.

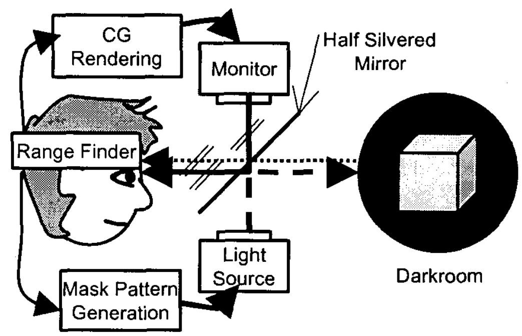


Figure 7. Pattern light source system.

3.3. Approach 2: Retro-reflective screen.

Inami et al. developed another system called a head mounted projector, using retro-reflective screens as a part of studies on object-oriented displays [10]. Figure 6 shows the configuration of the system. This approach uses real objects covered with retro-reflective material as screens that a synthetic scene is projected onto (methods [R2] and [V2]). That is, a synthetic image is cast to a real scene from a projector located optically equivalent to user's eye. Then, most rays that hit the screen reflect and go back to user's eye, while most rays that hit other real objects diffuse randomly and scarcely go back to user's eye. Consequently, mutual occlusion is realized, since virtual objects appear only on the retro-reflective screen and disappear in front of and behind the screen. With this approach, consistency between vergence and accommodation is kept when observing virtual images. However, this approach requires special real objects as screens, and virtual images are only seen on them.

3.4. Approach 3: Pattern light source.

Noda et al. developed a unique approach using a pattern light source [4]. Figure 7 shows the system configuration. First, a real-time range finder acquires a depth map of real objects that are located in a darkroom. Then, the real objects are lit by a projector partially only where they should appear (method [R1]). Finally, the pixels of virtual objects that are in front of real objects are rendered (method [V1,3]). Consequently, a user can see correct mutual occlusion from the range finder's point of view. With this approach, any rays of a real scene can be masked without special real objects. However, a darkroom is needed and its application area is strictly limited.

All of the previous approaches are well designed and each has a number of advantages. However, they all require special environmental settings. That is, outside the displays, the real world itself has to be modified physically. Some require special real objects and another requires a darkroom. All existing approaches are impractical for such applications that require wide working area or outdoor activity. Though the method [R4], which is often used in head-up displays of airplanes, can be used in outdoor, it strictly restricts available colors.

4. Optics Design

We have developed a novel approach that uses the method [R3]. Figure 8 shows a basic idea of the optics design. The heart of the new design is to put a liquid crystal display (LCD) panel in front of a conventional optical see-through display in order to block any rays coming from outside. This is not enough, however, since the LCD panel is so close to the eyes that a pattern on the panel gets out of focus when a user sees outside objects.

We conquered this problem by locating two convex lenses with one focal length f in front of and behind the LCD panel. This optics makes a telescope of one magnification. Finally, we use an erecting prism to erect inverted outside scenery. Figure 9 shows the optics design. With this optical system, a viewer can simultaneously observe both outside scenery and a pattern on the LCD panel in focus. By opening pixels on the LCD panel where real objects should appear and by shutting pixels on it where virtual objects should appear, mutual occlusion of real and virtual worlds can truly be presented optically. Notable three advantages of our approach are as follows:

1) *All-purpose:* Since the display does not affect the real environment nor require any additional environmental settings, it can be used anywhere in any situations including outdoor applications.
2) *Color fidelity:* Since the display can surely block any rays coming from outside scenery in any situations, virtual images keep their original intended color, and the fidelity is much more superior to conventional optical see-through displays.
3) *Compatibility:* Since the light-blocking part is separated with the display for color graphics, it can be used with most existing optical see-through displays.

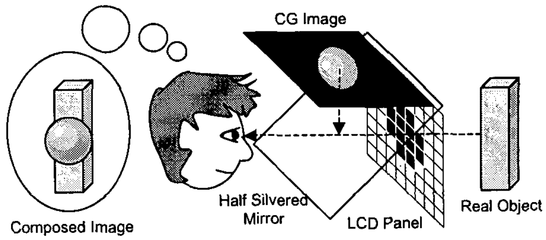


Figure 8. Basic idea of the optics.

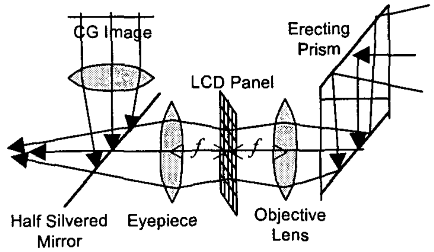


Figure 9. Optics design.

On the other hand, if we make this optics straightforwardly, it adds a certain amount of viewpoint offsets, causing inconsistency between proprioception and visual perception. We will show you how we want to solve this problem in Section 7.

5. Prototype System

Based on the basic design of the optics, we have built a prototype display to confirm the effectiveness of the approach. Figures 10 and 11 show an appearance and the blueprint of our first prototype display, respectively. We newly developed lenses and a prism, and employed a commercially available 10.4-inch LCD panel (Integral Electronic Japan, IDB-9344W). Specification of the optics is summarized in Table 1. Dot pitch of the panel is 0.27 [mm] and the effective area of the panel is 31x31 [mm]. So, this setup can display a mask pattern of about 120x120 pixels. Transparencies of open/closed pixels of the panel vary by changing resistance of the panel's circuit (see Figure 12), and we adjust them as 18 [%] and 2 [%] respectively so that the contrast is maximized.

Connecting the LCD panel directly to the RGB output of a PC (SGI VWS540), a black synthesized image can be displayed. For example, a black computer-graphics cylinder is piercing a real white cylinder and a real white box in Figure 13. In this case, real objects are modeled and calibrated manually, and LCD pixels are set to open only where the real image should appear by rendering transparent objects [3]. Like this, the prototype display can surely present black synthetic images, which cannot be realized with conventional optical see-through displays.

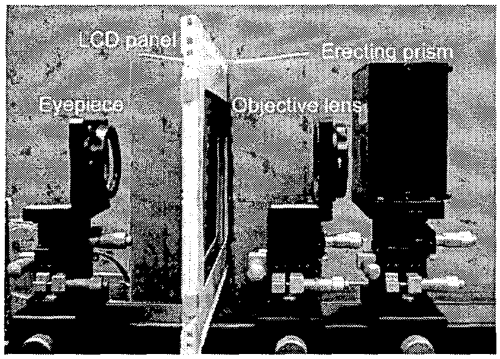


Figure 10. Appearance of the first prototype display.

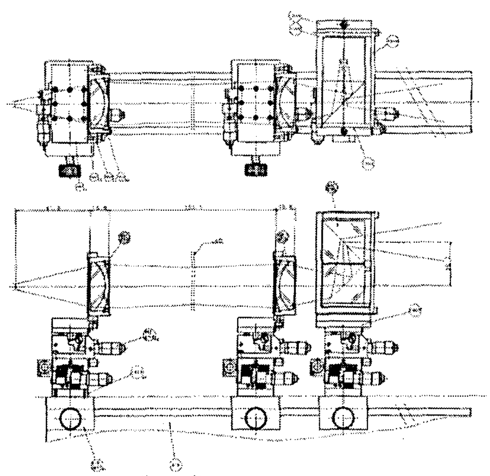


Figure 11. Blueprint of the first prototype display.

Table 1. Specification of the first prototype display.

Eyepiece/Objective lenses	
Focal length	70 [mm]
Effective aperture	37 [mm]
Center thickness	15.5 [mm]
Weight (for each)	56 [g]
Erecting prism	
Window shape	35 x 35 [mm]
Refractive index	1.755
Weight	273 [g]
Effective field of view	> 25 [degree]
Exit pupil aperture	> 5 [mm]
Eye relief	> 60 [mm]
Viewpoint offsets	
Horizontal	291.9 [mm]
Vertical	35.7 [mm]
Transparency/Reflectance	(lambda = 550 [nm])
Eyepiece	0.98
Objective lens	0.98
Erecting prism	0.92
Total	0.88

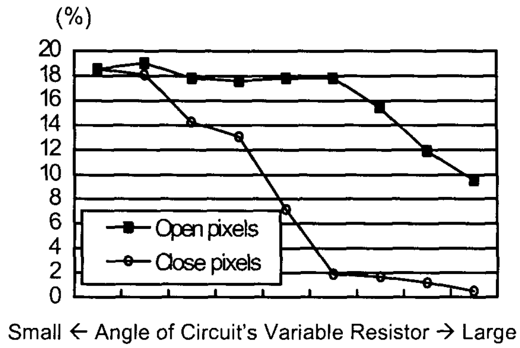


Figure 12. Transparency of the LCD panel.

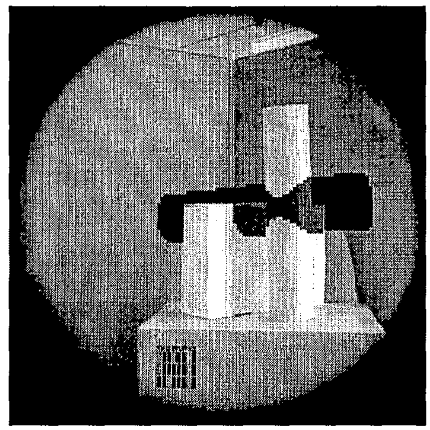


Figure 13. An image seen through the first prototype display.

On the other hand, due to the property of the LCD panel, lattice pattern between the pixels stand out, and real objects are not perfectly invisible for closed pixels. However, these problems can be relieved with another LCD panel commercially available of wider aperture and higher contrast.

6. Experiments

Figure 14 shows the prototype display with an optical see-through HMD (Shimadzu STV-E). Using the same PC, colorful virtual images are rendered to the HMD via PC's video output. A digital video camera (Sony DCR-TRV900) is used to capture the image seen through the display. Figure 15 illustrates the configuration of the experimental setup. All virtual objects and a white real box are modeled in advance (Figure 15(A)). The 3D magnetic tracker (Polhemus Fastrak) transmits position and orientation of the real box to the PC (Figure 15(B)). Then the PC renders a virtual scene composed of virtual objects including a counterpart of the real box (Figure

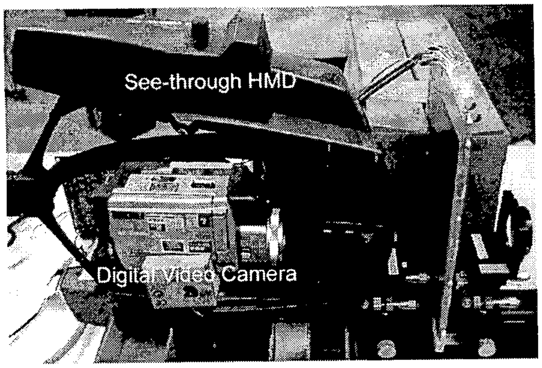


Figure 14. The first prototype display with an optical see-through HMD.

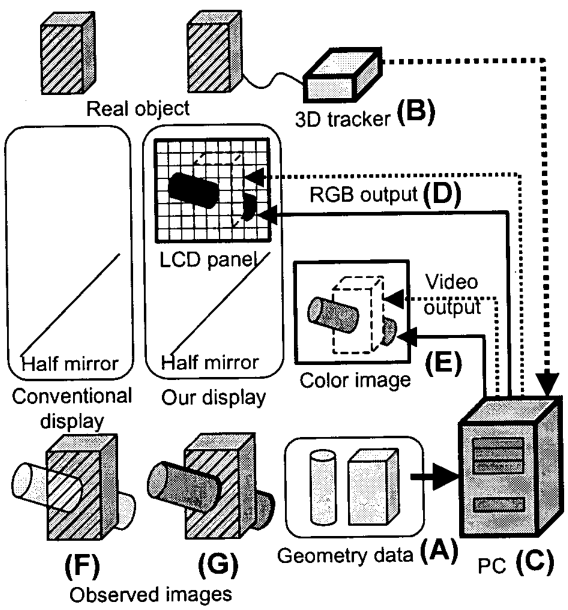
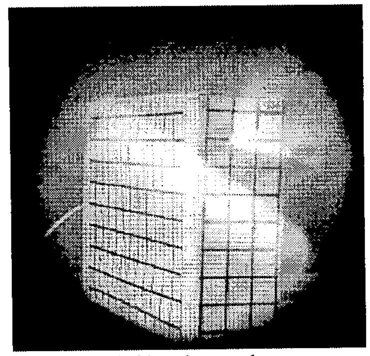


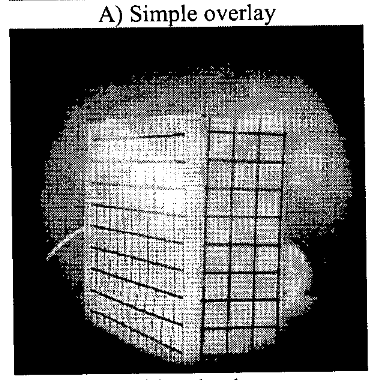
Figure 15. System configuration.

15(C)) twice, for a mask pattern (Figure 15(D)) and a color image (Figure 15(E)). Note that the counterpart of the real object is rendered transparently using the alpha-blending feature of OpenGL [3]. By doing this, z-buffer is appropriately modified according to the real object while keeping the corresponding pixels transparent. Combining this technique, a mask pattern can be easily rendered by disabling light effects and modifying colors. As a result, correct mutual occlusion is presented by our setup (Figure 15(G)), while conventional displays can only present a ghost image (Figure 15(F)).

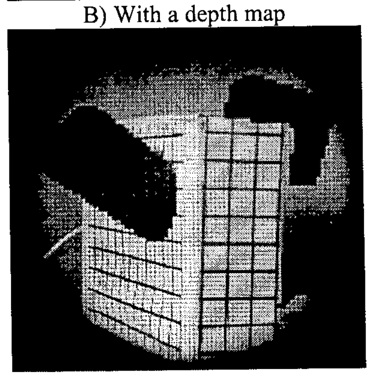
Figure 16 shows four images captured by this setup. Conventional optical see-through displays present an overlaid image like Figure 16(A). In this case, occlusion



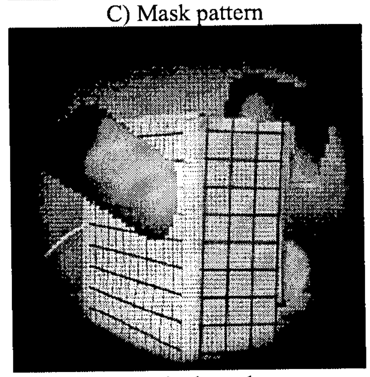
A) Simple overlay



B) With a depth map



C) Mask pattern



D) Final result

Figure 16. Four patterns of overlaid images seen through the first prototype display.

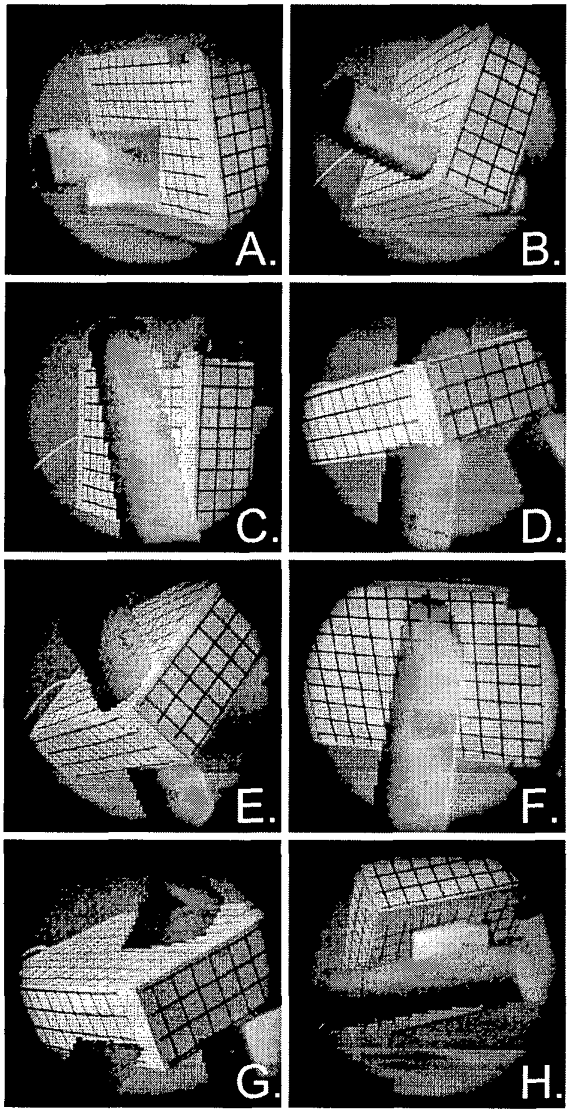


Figure 17. Real-time image overlay.

relationship is not presented so that you can hardly tell which portion of the virtual image is really in front of the real objects. With depth information of a real object, virtual objects can be covered with the real one (Figure 16(B)). However, they remain semitransparent ghosts and the real object behind the virtual image is still visible. On the other hand, our prototype display can block the real scene as shown in Figure 16(C). Finally, combining the mask pattern with colorful virtual images presented by a normal optical see-through display, a mixed world with correct occlusion and high color fidelity can be truly presented as shown in Figure 16(D).

Figure 17 shows eight snapshots of real-time image overlay. In this case, the observer sees the box being manipulated by another operator. As shown in the figure, mutual occlusion is properly realized for various situations. However, response time of the LCD panel is so slow (>150 [ms]) that mask pattern sometimes appears even after the color image was turned off. For example, the operator moved the white box so fast that a crescent-shaped portion of the mask pattern is remained lingeringly in Figure 17(F).

7. Conclusions and Future Work

This study is the very first step that seriously tried to tackle the well-known occlusion problem of optical see-through displays. In this paper, we first pointed out the occlusion problem of conventional optical see-through displays, and then proposed a novel optics design for optical see-through displays that can present mutual occlusion of real and virtual environments. This display design can be used anywhere including outdoor, and it enhances color fidelity of virtual images. We also presented our prototype display and showed experimental usage of the display. Through the empirical studies, we confirmed that our novel display design surely solved the occlusion problem.

However, some properties of the first prototype display are not necessarily sufficient. As for the optics, we have to make it stereoscopic and smaller, shorten the length of viewpoint offset, and enlarge the field-of-view. To solve some of these problems, we have already designed a compact version of the optics as shown in Figure 18. We are now building new display based on this optics design. An appearance of the outer frame and its blueprint are shown in Figures 19 and 20. This smaller optics allows a user to see a mixed reality environment stereoscopically without viewpoint offset.

As for the LCD panel, we have to improve its transparency, contrast, response time, and resolution. Though the light attenuation caused by the LCD panel is one of the inevitable problems of this approach, it may not a serious issue if scotopic adaptation functions well. As for the response time and resolution, we will be able to conquer these problems in the near future, for such LCD panels that have the response time of less than 2 [ms] and resolution of over 200 [dpi] are recently commercially available.

To make better use of our optics design, it would be useful to employ a real-time depth acquisition mechanism [3][4][5] and an accommodative compensation mechanism [11]. Our display would be effectively used in wide-area or outdoor, that requires some good tracking techniques [12][13]. We also would like to pursue these issues.

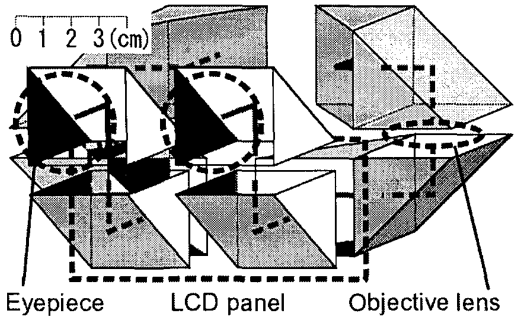


Figure 18. A compact optics design of the display.

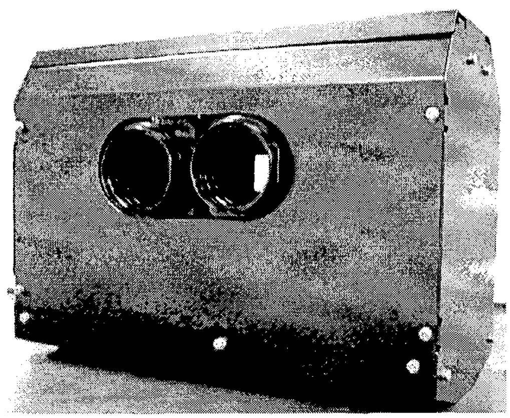


Figure 19. An appearance of the second prototype display.

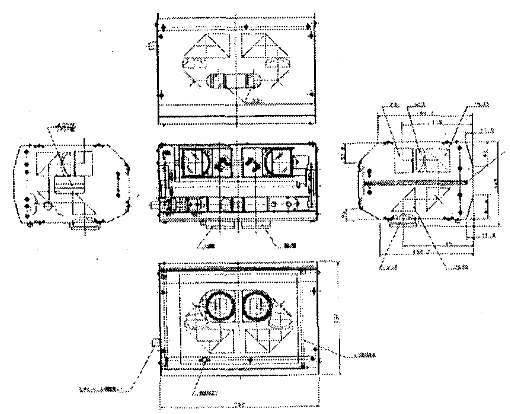


Figure 20. Blueprint of the second prototype display.

8. References

[1] Yuichi Ohta and Hideyuki Tamura (ed.), Mixed Reality, Ohmsha, 1999.

[2] A. B. Sekuler and S. E. Palmer, "Perception of Partly Occluded Objects: A Microgenetic Analysis," Journal of Experimental Psychology: General, Vol. 121, pp.95-111, 1992.

[3] Masayuki Kanbara, Takashi Okuma, Haruo Takemura and Naokazu Yokoya, "A Stereoscopic Video See-through Augmented Reality System Based on Real-time Vision-based Registration," Proc. of the IEEE VR 2000, pp.255-262, 2000.

[4] Shinichi Noda, Yoshihiro Ban, Kosuke Sato and Kunihiro Chihara, "An Optical See-Through Mixed Reality Display with a Realtime Rangefinder and an Active Pattern Light Source," Trans. of the Virtual Reality Society of Japan, Vol.4, No.4, pp.665-670, 1999 (in Japanese).

[5] Kanade, T., Yoshida, A., Oda, K., Kano, H. and Tanaka, M., "A Stereo Machine for Video-rate Dense Depth Mapping and Its New Applications," Proc. of CVPR '96, pp.196-202, 1996.

[6] Ronald T. Azuma, "A Survey of Augmented Reality," MIT Press Presence, Vol.6, No.4, pp.355-385, 1997.

[7] Hirokazu Kato and Mark Billinghurst, "Marker Tracking and HMD Calibration for a Video-based Augmented Reality Conferencing System," Proc. of the IEEE & ACM IWAR '99, pp.85-94, 1999.

[8] Kiyoshi Kiyokawa, Yoshinori Kurata and Hiroyuki Ohno, "An Optical See-through Display for Mixed Reality," Proc. of the ACM SIGGRAPH, Conference Abstracts and Applications, p.241, 2000.

[9] Ken-ichi Kameyama, "Tangible Modeling System," Proc. of the ACM SIGGRAPH '99, Conference Abstracts and Applications, p.279, 1999.

[10] Masahiko Inami, Naoki Kawakami, Dairoku Sekiguchi, Yasuyuki Yanagida, Taro Maeda and Susumu Tachi, "Visuo-Haptic Display Using Head-Mounted Projector," Proc. of the IEEE VR 2000, pp.233-240, 2000.

[11] S. Shiwa et al., "A New Binocular Parallax Display Method in which Vergence Changes are Linked to Accommodative Response," Proc. of Asia Display '95 Technical Digest, p.785, 1995.

[12] Welch, G., Bishop, G., Vicci, L., Brumback, S., Keller, K. and Colucci, D., "The HiBall Tracker: High-Performance Wide-Area Tracking for Virtual and Augmenred Environments," Proc. of the ACM VRST '99, pp.1-10, 1999.

[13] Ronald Azuma, Bruce Hoff, Howard Neely III, and Ron Sarfaty, "A Motion-Stabilized Outdoor Augmented Reality System," Proc. of the IEEE VR '99, pp.252-259, 1999.