Visuo-Haptic Display Using Head-Mounted Projector

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Abstract

This paper proposes a novel visuo-haptic display using a head-mounted projector (HMP) with X'tal Vision optics.

Our goal is to develop a device which enables an observer to touch a virtual object just as it is seen.

We describe in detail the design of an HMP with X'tal Vision which is very suitable for augmented reality. For instance, the HMP makes the occlusion relationship between the virtual and the real environments nearly correct. Accordingly, the user can observe his/her real hand with the virtual objects. Furthermore, the HMP reduces eye fatigue because of the low inconsistency of accommodation and convergence.

Therefore, we applied HMP-model 2 to a visuo-haptic display using a camouflage technique.

This technique, called optical camouflage, makes an obstacle object such as a haptic display become translucent.

With this method, a user can observe a stereoscopic virtual object with a nearly correct occlusion relationship between the virtual and the real environments and can actually feel the object.

1. Introduction

Active Environment Display (AED) [1] and PHANToM [2] are typical examples of virtual reality haptic displays.

A head-mounted display (HMD) is commonly used to overlay virtual space and haptic space.

A standard closed-view HMD does not allow one to view the real world directly. Hence the viewer can observe only the virtual world. Unfortunately, the resolution of the HMD's image is not high enough to perceive the immediate reality.

An optical see-through HMD, which is usually used to construct augmented reality, is also useful to combine visual space and haptic space.

However, there are some problems in displaying haptic images and visual images simultaneously. One of the problems is the difference in occlusion, which causes a disparity between real and virtual objects when using a sensory display, such as a haptic display, or a human-status sensor, such as a position sensor. Namely, the display unit, the sensor and the human body hide the visual image. Thus the reality is partly lost.

When we consider displaying the objects in a VR system, this problem becomes critical since the occlusion is one of the most important keys to perceiving stereoscopic depth.[3]

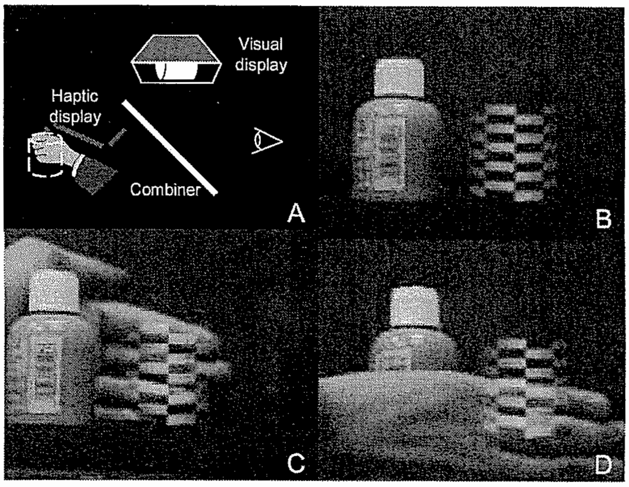


Fig. 1 Difference in occlusion A : Optical see-through configuration; B-D : Observed images

Fig. 1 shows an example of difference of occlusion.

In the figure, (A) depicts the principle of optical-see-through-based visual haptic integrated display.

A real object and a virtual object are placed at the same depth.(B)

When you place your hand behind the two objects, you can still see it through the virtual object, while the real one occludes the hand.(C)

Similarly, when you put your hand in front of the two objects, only the real one is correctly occluded.(D)

The purpose of this paper is to solve the above problems by using a head-mounted projector (HMP). The design and the implementation of the HMP are discussed in the following section.

2. Previous work

Various methods have been proposed to integrate visual and haptic space.

The problem of the difference in occlusion can be avoided by setting up a force display in front of a visual display.

A Nano workbench [4] and tangible holography [5] consist of a stereoscopic display and a PHANToM being arranged in this way. However, the force display itself occludes a visual image which, in many cases, is located very close to the target with which it interacts.

SPIDAR [6] solves this occlusion problem by using tensed strings. However, the virtual object cannot occlude the real object.

A haptic screen [7] is a nearly ideal implementation of a visuo-haptic display. An image of the virtual object is projected onto the elastic surfaces, which deforms by itself to present shapes of the virtual object. Thus a user can directly touch the image and can feel it firmly. However, this system can display only smooth surfaces and the virtual object cannot occlude the real object.

WYSIWIF display [8] and PDDM [9] are other implementations of visuo-haptic display. The occlusion effect of the system is very similar to our system.

A WYSIWIF display is one of the video see-through displays which solves the occlusion problem by using chroma-key. In this system, a force display is covered with blue clothes. By using the video see-through technique, the resolution of the image of real space such as the operator's hand, is limited by that of a camera or a display apparatus.

PDDM uses an LCD display as an end-effector of a manipulator. Therefore, a user can handle and observe a virtual object. However, PDDM cannot display stereoscopic images.

3. Head-Mounted Projector with X'tal Vision

Recently, a novel virtual/augmented Reality display apparatus, head-mounted projector (HMP) with retroreflective screen, was proposed. [10][11][12][13][14]

We also developed a similar optics configuration named X'tal Vision (Crystal Vision) in order to apply the projection-based object-oriented display from an independent standpoint.[15][16][17]

3.1 X'tal Vision

The following are the three key techniques of X'tal Vision:

1. An object covered with retroreflective material is used as a screen;
2. A projector is placed at the position optically conjugated with the observer's eye by using a half-mirror;
3. The projector's iris is very small.

Each of these techniques provides the following advantages, respectively:

1. The observer can handle objects of arbitrary shape, looking at bright images projected on the surface of the object covered with retroreflective material;
2. There is no distortion of image, regardless of the shape of the screen;
3. Larger depth of field is obtained so that the screen can be located any distance from the projector.

Moreover, the combination of the above techniques provides this system with additional merits:

- The brightness of the image is independent of the change in distance between the projector and the screen (1+2);
- The observer's hands and the real objects correctly occlude the displayed object (1+3);
- Stereoscopic images are obtained(1+2+3).

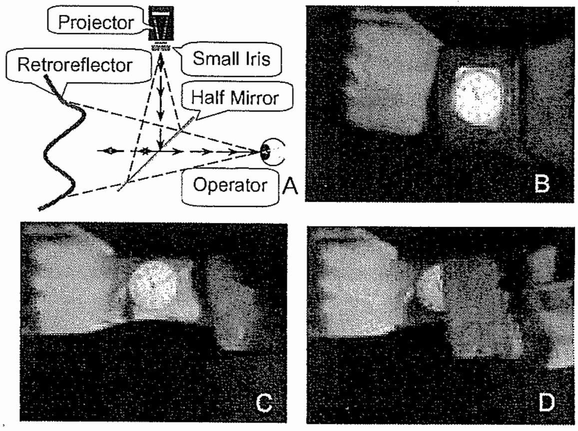


Fig. 2 A: Principle of X'tal Vision; B: Virtual watch with optical see-through (not occluded by sleeve); C: Virtual watch with X'tal Vision; D: Virtual watch with X'tal Vision (occluded by sleeve)

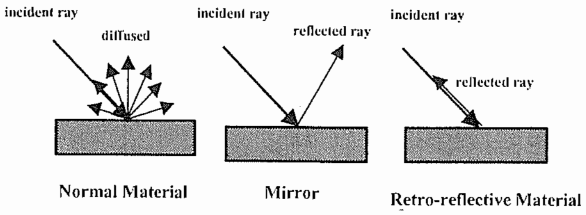


Fig. 3 Retroreflective material

Fig. 2 shows the principle of X'tal Vision. The projector with a small iris projects the image of the virtual object. The projected image is reflected by a half-mirror at a right angle and retroreflected on the retroreflective screen. Normal and retroreflective materials differ in the following ways. In the case of normal material, a ray of light incident on the surface diffuses. In the case of retroreflective material, an incident ray reflects at a similar angle to the angle of incidence (Fig. 3).

Each of these features of X'tal Vision is well known. We integrated these features and produced a new effect which is suitable for VR/AR.

3.2 Occlusion relationship

We used a pinhole as the projector's iris in order to obtain a perfectly focused image. However, the projected image through the small aperture on a normal surface is too dim to be perceived by human eyes.

The light coming out from the projector is reflected on the half mirror and then on the screen. It goes straight back to the eye to form the image, which is about ten to one hundred times brighter than the image on the normal surface. Therefore, the image only appears only the retroreflective material so that the viewer can observe it as if the image projected on the retroreflective material were occluded by the object which exists in front of the screen.

Projecting onto a retroreflective screen is a traditional method in the field of motion pictures and television.

This method, as applied to special effects, was named front projection in the 1960s and was common until chroma-key became widely used. It is said that *2001: A space odyssey* (1968) was the first film to use the front projection effect.

Today chroma-key is an essential tool for special effects. Actually, chroma-key is superior to front projection in terms of contrast and accuracy of keying. However the front projection effect combines images very quickly at the speed of light. Images projected by this method can be observed with the naked eye. Thus similar techniques have been used in the field of VR in recent years.

However, this method has the following problem. When a real object is in front of the screen, the virtual object projected on the screen is correctly occluded by an outline of the real object. On the other hand, when the screen is in front of the real object, the real object is not occluded by the shape of the virtual object but by that of the screen.

Therefore, it is desirable to use a screen which has a shape and location similar to that of the projected virtual object, as in the object-oriented display.[16]

3.3 Inconsistency of Accommodation and Convergence

HMP can also solve HMD's inherent problem: the inconsistency of accommodation and convergence.

Binocular disparity and convergence are very important for stereopsis. Many stereoscopic displays, including HMD, use a binocular stereogram.

It is necessary in an ideal stereoscopic display that various conditions (e.g. convergence, accommodation and object size on the retina) correspond between the real image and virtual image. But conventional HMD's focus point is fixed on the distance of 1m or 2m. Then these HMD have inconsistent accommodation against convergence.

Accommodation and convergence affect each other, and the effect is observed as accommodative convergence and convergence accommodation.[18]

We can change convergence comparatively with fixed accommodation.

If a viewer wants to show an object out of the image plane, he/she has to show these places on the image plane.

Therefore, while the distance where the image is really seen, the distance of the focus point and the distance to the object towards which the eyes converge are usually equal, this case presents a severe inconsistency, a cause of eye fatigue.

Furthermore, inconsistent accommodation against convergence causes inaccurate measurement of distance. This problem is especially serious with see-through HMD because the observer cannot focus both real the image and the CG image.

The valuable focus display was proposed to solve the problem.[19] Unfortunately, the method has other problems. For example, the display needs complex optics, an eye-tracker and depth images.

The problem of inconsistency is solved in the following way.

By using HMP with X'tal Vision, the distance between the screen and the object is kept small so inconsistency also stays small. This has an additional merit. In traditional display system, the inconsistency is not only large, but it varies as the virtual object moves. In the case of the HMP, it does not change even if the virtual object moves.

3.4 Design of a depth of field of HMP

The design of X'tal Vision puts the priority on depth of field by using a small iris.

Many conventional HMPs have a potential problem with small depth of field, which limits the range of distance between the HMP and the screen.

A small iris is placed in front of the projector to secure adequate depth of field. Then a user wearing an HMP can observe focused images on a screen placed at any distance. However, if the iris is too small, the resolution of the projected image becomes lower because of diffraction.

In this section, quantitative analysis of the small iris effect is provided. If the projector has enough brightness, the limit of the resolution is determined by the aperture size. (In addition, Fraunhofer diffraction images on the focal point cause lower resolution.) In this case, it is assumed that the projector has no aberrations.

The intensity distribution produced by Fraunhofer diffraction of a circular hole can be represented as follows:

$$I(r) \propto \frac{1}{\lambda f}\left[\frac{2J_1\left(\frac{\pi\Phi r}{\lambda f}\right)}{\frac{\pi\Phi r}{\lambda f}}\right]^2 , \qquad (1)$$

where I is the intensity distribution, r is the distance from the axis, λ is the wave length, J_1 is the first order Bessel Function, Φ is the diameter of the iris and f is the focus length.

This distribution pattern is known as an Airy disk, and the radius of the first dark ring defines the Rayleigh limit.

$$r = \frac{1.22\lambda f}{\Phi} \qquad (2)$$

The angular resolution is then defined as Θ, which can be approximated to $\Theta \approx r/f$ when $\Theta << 1$, thus

$$\Theta \approx \frac{1.22\lambda}{\Phi} \qquad (3)$$

Concerning the relationship between the diameter of the iris and the depth of field, if the required angular resolution is Θ, the range of the depth of field of the optics of Fig. 4 is between $f_{near} = \frac{f\Phi}{\Phi + f\Theta}$ and $f_{far} = \frac{f\Phi}{\Phi - f\Theta}$.

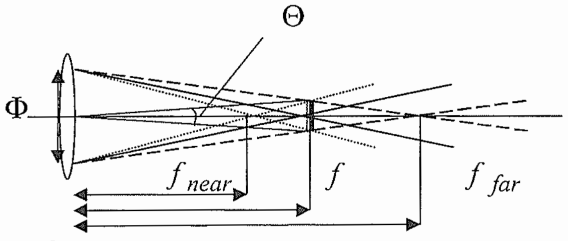


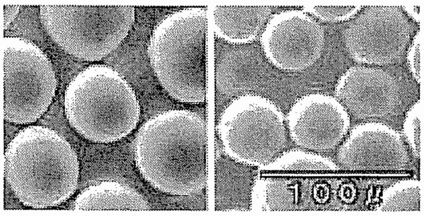
Fig. 4 Depth of field of the optics

By using equations (2) and (3), it is possible to determine the diameter of the iris and the distance of the screen. For example, a projection-based system, which requires $\Theta = 1.0 \times 10^{-3}$ [rad] as the angular resolution, requires an iris with a diameter Θ of more than 0.67[mm]. This iris makes the range of the depth of field between $f_{near} = 0.34$[m] and $f_{far} = \infty$[m] when the focal point is 0.67[m]. Specifically, a user wearing HMP with the preceding optics can change the distance of the screen from 0.34[m] to ∞[m]. However, this estimation does not take into account the brightness of the projected image, which will not be discussed here.

3.5 Retroreflective screen for HMP

One of the technical characteristics of X'tal Vision is the use of the retroreflector as a screen. In this section, we describe the retroreflective screen. Three kinds of retroreflective materials are generally known, namely corner-cube arrays, fly-eye lenses with diffusers and micro-beads. For the purpose of our study, micro-beads were selected because they easily make various screen shapes. Micro-beads with a refractive index of 2.0 have a retroreflective character. Moreover, there are two kinds of micro-bead-type retroreflectors cloth-type and paint-type. (Left: Cloth-type; Right: Paint-type)

Fig. 5 shows the SEM images of cloth-type and paint-type retroreflectors. The diameter of each bead is about 50[μm]. A micro-bead-type screen placed at a distance of more than 34[cm] from the eye/projector has enough resolution because the normal angular resolution of the human eye is less than about 1.5×10^{-4} [rad].



(Left: Cloth-type; Right: Paint-type)

Fig. 5 SEM images of micro-bead-type retroreflector

The reduction of reflecting light according to the angle of reflection was measured. The reflection directivity was less than 1.1-degrees. This means that a user of an HMP can observe a stereoscopic image on a retroreflective screen if the distance between an HMP and a projector is less than 3.3[m]. (The distance between each eye is assumed to be 63[mm]). If the user wants to observe a stereoscopic image on a further screen, we suggest attaching a polarizing filter to the HMP to split right and left images. Actually, corner-cube arrays do not keep polarizing, but micro-beads or fly-array lenses with diffusers secure to keep polarizing.

Fig. 6 shows the relativity of the angle of incidence, which indicates that paint-type micro-beads have a wider viewing angle.

The reason is that paint-type micro-beads result in the complex porous surface of paint-type micro-beads. (Fig. 7)

The wide viewing angle of the screen makes the user's and/or screen's place free. It also makes screen's shape free. A normal screen has to be a cosine falloff with angle to the user. However, paint-type micro-beads do not work according to that falloff. Therefore, the image dimming on the edges of curved objects is less affected than that on the edges of a normal surface.

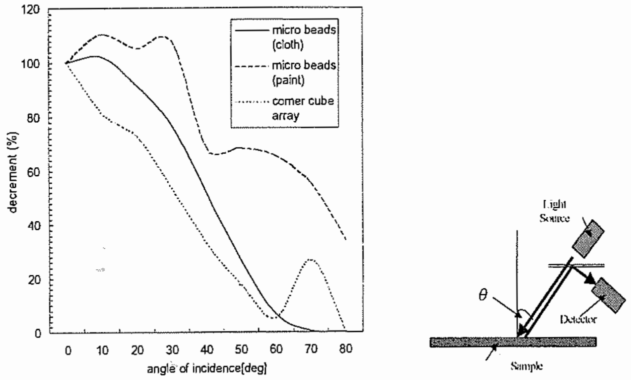


Fig. 6 Relativity of angle of incidence

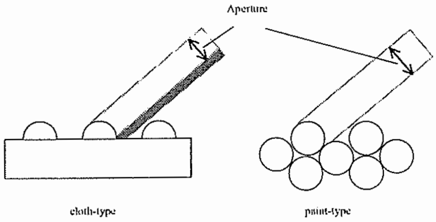


Fig. 7 Aperture size against oblique incident lay

The merits and demerits of retroreflective materials are tabulated in Table 1. As these results suggest, paint-type micro-beads are usually the best choice for screen used with HMP. However, if HMP applies only a flat screen, cloth-type micro-beads or corner-cube arrays are worth considering.

Table 1 Comparison of retroreflectors

Material	Merits	Demerits
Corner-cube array	● precise retro-reflection ● high reflectance	● narrow viewing angle ● only flat shape
Fly-eye lens with diffuser	● high reflectance	● narrow viewing angle ● only flat shape
Micro-beads	● wide viewing angle ● arbitrary shape	● inadequate retroreflection

3.6 Registration

Standard closed-view HMD configuration doesn't require precise registration of visual and haptic space. Psycho-physiology suggests that reaching movements without the sight of the limb have an error of a few centimeters, which seems to be unavoidable.[20]

On the other hand, the acceptable error with the sight of the limb is less than two millimeters. Thus the see-through HMD must be precisely registrated.

HMP also requires correct registration. Consequently, the position of HMP should be measured with a high-speed, high-resolution, jitter-free and low-latency sensor.

Hence, we developed the 6 D.O.F. mechanical position sensor with a counterbalance mechanism and a calibration jig.

3.7 HMP model-2

In the configuration of X'tal Vision, screen shapes are arbitrary. This is due to the characteristics of the retroreflector and the small iris in the conjugate optical system. By using the characteristics of X'tal Vision, binocular stereovision make it possible to use an arbitrary shape as in Fig. 8. This system should be mounted on the head of the user as an HMP.

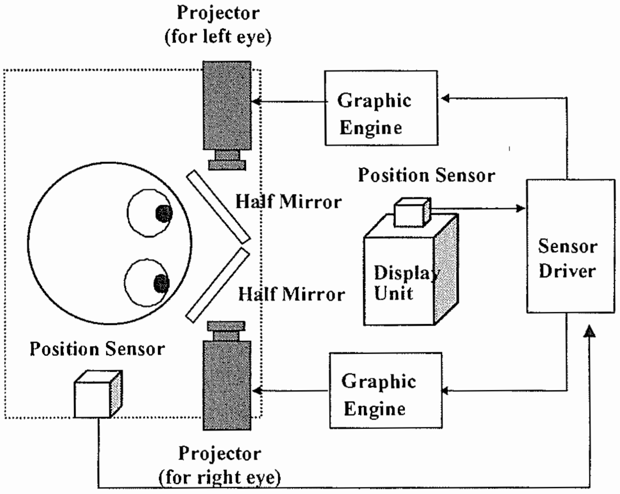


Fig. 8 Principle of a Head-Mounted Projector (HMP)

Fig. 10 shows the second prototype of HMP. Two liquid crystal display panels (0.7[inch] diagonal, 832x624 non-interlaced) are mounted on a helmet. A fiber-guided light source is fixed above the LCD panels. A C-mount camera lens (12.5[mm] focal length) projects the image with a wide angle (horizonal:60[deg]). Eye relief is long enough (70 [mm]) to wear the HMP with glasses.

The weight is 1650[g]. The weight is balanced with a counterweight and constant force springs using a wire-pulley mechanism.

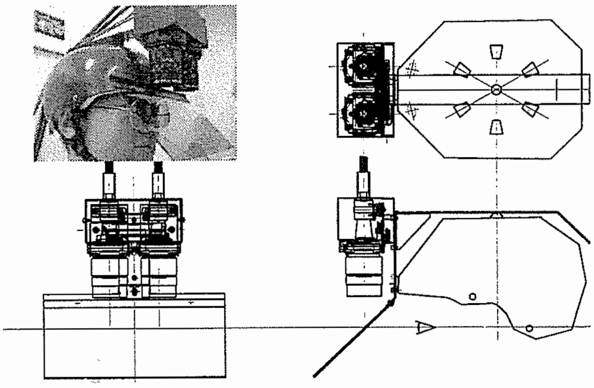


Fig. 9 HMP model-2

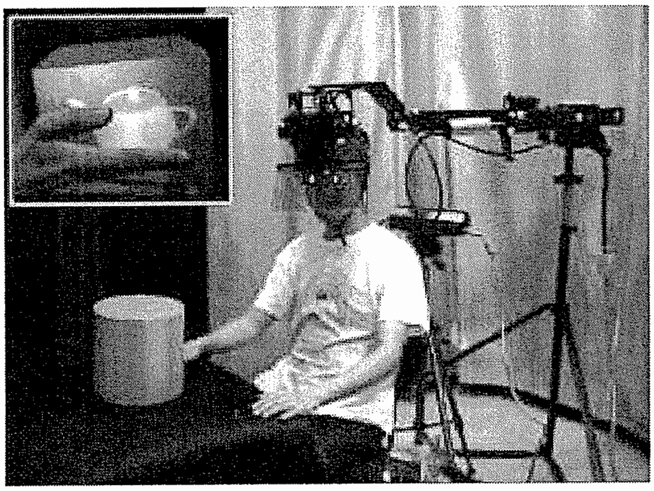


Fig. 10 HMP model-2 with mechanical 6 D.O.F. position sensor and projected image

Fig. 10 shows an example of an image projected on a screen covered with retroreflective material with accurate occlusion relationships. The image can be clearly observed under room light (about 200[lx]). This projection method does not require a darkroom. The user can observe the projected image while working in a real environment.

4. Visuo-Haptic Display Using Head-Mounted Projector

4.1 Optical Camouflage

For visuo-haptic display, camouflaging a real object is as important as displaying a virtual object.

Most force displays consist of mechanical devices, which occlude virtual objects. This occlusion problem occurs near the target object, where the operator has to see more clearly. Moreover, the haptic device occludes not only the virtual object but also the real environment in the background.

By using an HMD, the operator can observe the virtual object clearly. However, he/she cannot observe his/her real hand. This problem obstructs the sensation of presence.

To solve these problems, we propose optical camouflage using X'tal Vision optics.

Fig. 11 shows the implementation of optical camouflage for a virtual scene. The object that needs to be made transparent is painted or covered with retroreflective material. Then a HMP is built. In the case of a virtual scene, the retroreflective screen is also set at the back, and the image of the virtual scene is projected.

Optical camouflage makes the masked object virtually transparent. Moreover, to project a stereoscopic image, the observer looks at the masking object more transparent.[21]

Optical camouflage can be applied for a real scene.

In the case of a real scene, a photograph of the scene is taken from the operator's viewpoint, and this photograph is projected to exactly the same place as the original. An example of optical camouflage for a real scene is shown in Fig. 12. Applying HMP-based optical camouflage to a real scene requires some image-based rendering techniques.

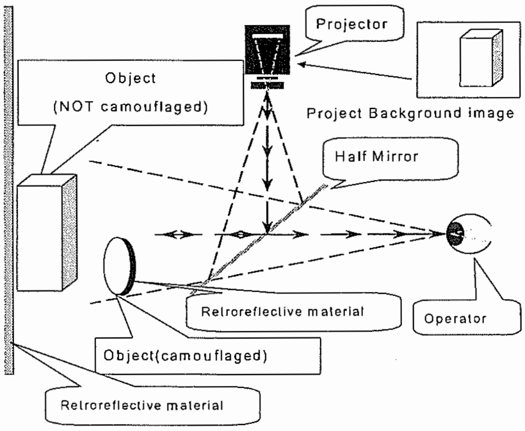


Fig. 11 Implementation of optical camouflage

In this case, a brick covered with a retroreflector hides a bookshelf. When the background image is projected onto the brick, the brick becomes transparent. Actually, the background image is projected not only on the brick but also on the other place. However, the image, which is projected on all places except on the brick, is too dark to perceive. Thus, only the brick looks transparent.

Fig. 12 Example of optical camouflage for a real scene

4.2 Prototype Visuo-Haptic Display

We applied optical camouflage to a visuo-haptic display. Fig. 13 shows the principle of an object-oriented visuo-haptic display.

We used HMP model-2 for the visual display part and PHANToM Desktop for the haptic display part. The haptic display was covered with a retroreflector.

A PC-based control unit and a graphic engine receive both the operator's hand position and his/her head position.

As a result, the virtual environment is projected from the HMP onto both the haptic display and the retroreflective screen. The other hand, the haptic display is controlled simultaneously. Hence the observer can touch the virtual object as it is seen.

Fig. 14 shows that haptic display (real object) hides the virtual object, but optical camouflage techniques permit the haptic display to become transparent. However, the operator's hand is NOT made transparent, which implies that it is possible to use this technique selectively.

Actually, the haptic display does not become perfectly transparent. The shape of the haptic display is observed clearly. Nevertheless, it looks like a very low refractive index glasswork, which is enough to allow one to observe behind the image.

This configuration has one difficulty. The operator is not allowed to touch the back of the virtual object with a correct occlusion relationship. We plan to develop an object-oriented visuo-haptic display.

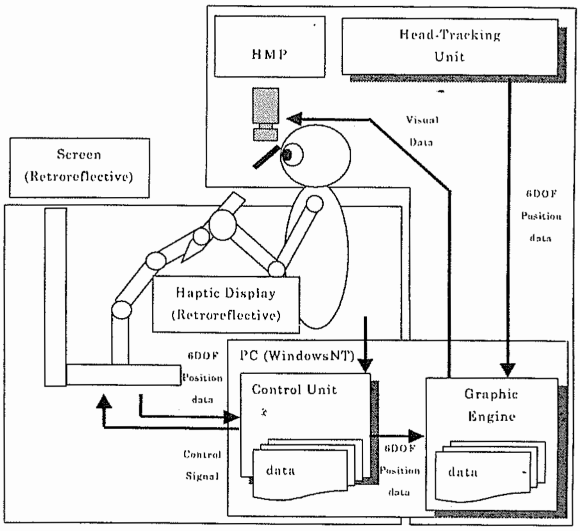


Fig. 13 Principle of a visuo-haptic display using a head-mounted projector

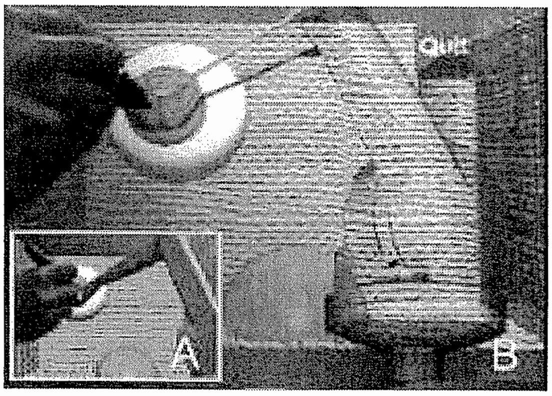


Fig. 14 Optical camouflaged PHANToM A: Before Camouflaged; B: After Camouflaged

5. Conclusion

In this paper, we described how an HMP with X'tal Vision is suitable for visuo-haptic display.

The design method and procedures of the HMP were clarified, and a prototype of an HMP was developed based on the design procedure.

The HMP user can observe stereoscopic images with a correct occlusion relationship between the virtual and the real environments. In addition, the image on the retroreflective screen is bright enough to observe virtual objects under a the room light. The wide depth of focus provided by the small iris on which the projector is placed allows for multiple screen arrangements and shapes.

Our method solves the occlusion problem in part and decreases the effect of inconsistency of accommodation and convergence.

We have succeeded in camouflaging force displays which obstruct visual images. The viewer is able to observe an object as if the force display were transparent.

We found that the roll axis of the 6 D.O.F. mechanical head-tracking sensor doesn't provide a precise position because of the low stiffness of the gimbals. We are planning to improve this.

6. Acknowledgement

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