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

We describe the detail design of an HMP with X'tal Vision, which is very suitable for Augmented Reality. For instance, the HMP makes almost-correct occlusion relationship between the virtual and the real environment. Accordingly, the observer can observe his/her real hand with the virtual objects. Furthermore, the HMP reduce eye fatigue, because of low inconsistency of accommodation and convergence.

Therefore, we applied HMP-model 2 to a visuo-haptic displays with the camouflage technique.

This technique is called Optical Camouflage. This technique makes an obstacle object like a haptic display become translucent.

By using this method, a user can observe a stereoscopic virtual object with almost-correct occlusion relationship between the virtual and the real environment and can actually feel it.

1. Introduction

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

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 reality at the moment.

An optical see-through HMD, which is usually used to construct Augmented Reality, is useful to combine visual space and haptic space, too.

Although quite useful, there are some problems to display haptic images and visual images simultaneously. One of the problems is the difference of occlusion which causes a disparity between real and virtual objects when using a sensory display such as haptic display or a human status sensor such as 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 perceive stereoscopic depth.[3]

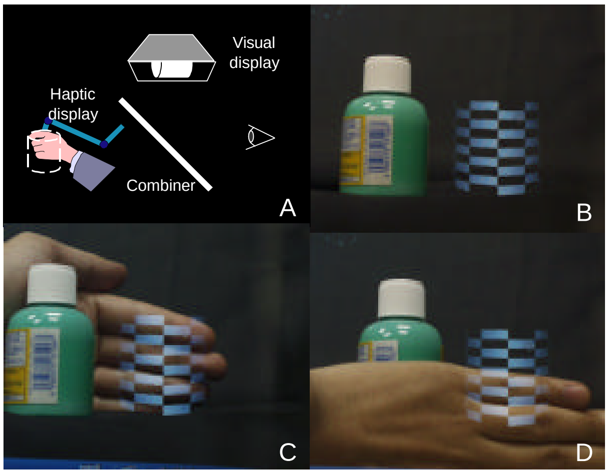


Fig. 1 Difference of occlusion, A : Optical see-through configuration, B-D : Observed images

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 one while the real one occludes the hand.(C)

Similarly, when you put your hand before 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 of occlusion can be avoided by setting up a force display in front of a visual display.

NanoWorkbench [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, locates very close to the target to interact with.

SPIDAR [6] solved this occlusion problem by using tensed strings. However, the virtual object can not occlude the real object.

Haptic screen [7] is the almost-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 surface and the virtual object can not 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.

WYSIWIF display is one of the video see-through displays, which solved 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 can not display stereoscopic image.

3. Head-Mounted Projector with X'tal Vision

Recently, a novel Virtual/Augmented Reality Display apparatus, Head-Mounted Projector (HMP) with retroreflective screen is proposed. [10][11][12][13][14]

We also developed 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 retro-reflective material is used as a screen;
2. A projector is placed on 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 retro-reflective 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 at 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 of the 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).

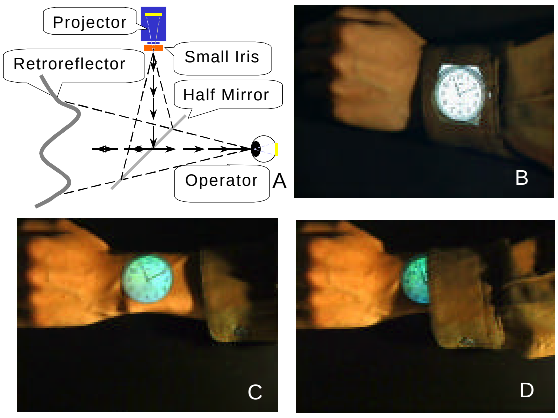


Fig. 2 A: Principle of X'tal Vision, B: Virtual watch with optical see-through (not occluded by sleeve), C: Virtual watch with X'tal Vision , D: Virtual watch with X'tal Vision (occluded by sleeve)

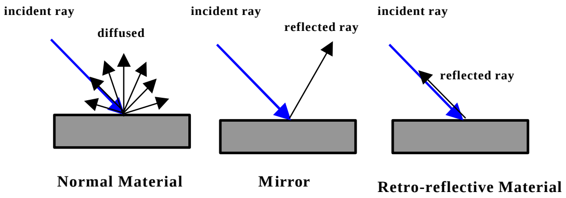


Fig. 3 Retroreflective material

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 on the right angle and retroreflected on the retroreflective screen. Normal and retroreflective materials differ in the following. 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 (See Fig. 3).

Each of these features of X’tal Vision is well known. Furthermore, 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. Furthermore, the projected image through the small aperture on the normal surface is too dim to be perceived by human eyes.

However the light coming out from the projector is reflected on the half mirror then on the screen and goes straight back in the eye to form the image, which is about ten or hundred times brighter than the image on the normal surface. Therefore the image only appears on the retroreflective material so that the viewer can observe as if the images projected on the retroreflective material are 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 contrast and accuracy of keying. However the front projection effect combines images very quickly at the speed of light. Images of that method are able to 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 real object is in front of the screen, virtual object projected on the screen is correctly occluded by 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 the similar shape and location of the projected virtual object such as the manner of Object-Oriented Display.[16]

3.3 Inconsistency of Accommodation and Convergence

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

Binocular disparity and convergence are very important key for stereopsis. Then many stereoscopic displays include HMD are using binocular stereogram.

It is necessary an ideal stereoscopic display that various conditions (e.g. convergence, accommodation and object size on the retina) correspond between 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]

Therefore we can change convergence comparatively with accommodation fixed.

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

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

Furthermore, inconsistent accommodation against convergence makes mistake to measure the distance. Especially this problem is more serious with See-through HMD. Because the observer can’t focus both real image and CG image.

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

The problem of inconsistency is solved in following way.

By using HMP with X’tal Vision, the distance between the screen and the object is kept small so inconsistency stays small too. 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 a depth-of-field by using a small iris.

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

$$I(r) \propto \frac{1}{lf}\left[\frac{2J_1\left(\frac{p\Phi r}{lf}\right)}{\frac{p\Phi r}{lf}}\right]^2 , \tag{1}$$

where I is the intensity distribution, r is the distance from the axis, l 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.

$$r = \frac{1.22\,lf}{\Phi} \tag{2}$$

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

$$\Theta \approx \frac{1.22\,l}{\Phi} \tag{3}$$

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 $f_{far} = \frac{f\Phi}{\Phi - f\Theta}$.

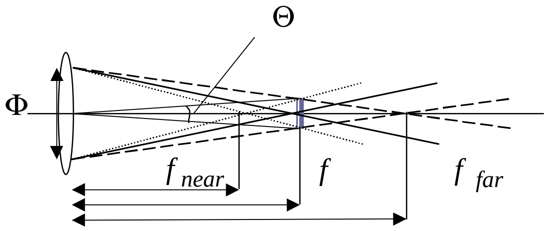


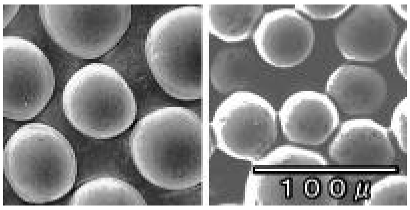
Fig. 4 Depth of field of the optics

By using the 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 $\Theta = 1.0\times10^{-3}$ [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 from the screen from 0.34[m] to ∞ [m]. However, this estimation does not take into account the brightness of the projected image, and we don't discuss about it 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 are easy to make various screen shapes. Micro-beads with the refractive index of 2.0 have a retroreflective character. Moreover, there are two kinds of micro-beads-type retroreflector, namely cloth-type and paint-type. (left: cloth-type, right: paint-type)

Fig. 5 is the SEM images of cloth-type and paint-type retroreflector. The diameter of the beads is about 50[m m]. Micro-beads-type screen placed at the 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-beads-type retroreflector

The reduction of reflecting light according to the angle of reflection was measured. The reflection directivity is less than 1.1-degree. This result 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 on the HMP to split right and left images. Actually, corner cube arrays does 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 wider viewing angle.

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

Wide viewing angle of the screen makes the user's and/or screen's place freely. And it also makes screen's shape free. Normal screen has to be a cosine falloff with angle to the user. However, paint-type micro-beads are not according to that falloff. Therefore, the image dimming on the edges of curved objects is smaller affected than that on the edges of normal surface.

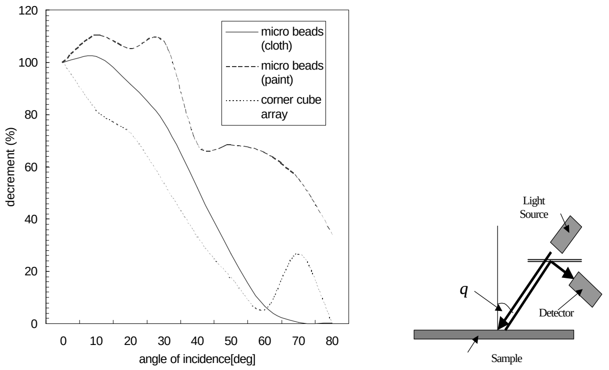


Fig. 6 Relativity of angle of incidence

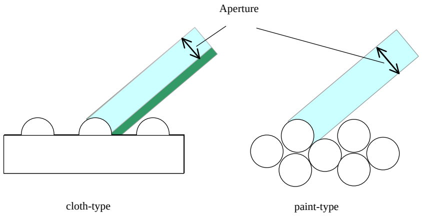


Fig. 7 Aperture size against oblique incident lay

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

Table. 1 Comparison of retroreflector

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 the visual and haptic space. The result of psycho-physiology suggests that the 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 the correct registration. Consequently, The position of HMP should be measured with high-speed, high-resolution, jitter-free and low-latency sensor.

Hence, we developed the 6 D.O.F. mechanical position sensor with counter balance 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 stereo vision becomes possible to use an arbitrary shape as in Fig. 8. This system should be mounted on the head of the user as an HMP.

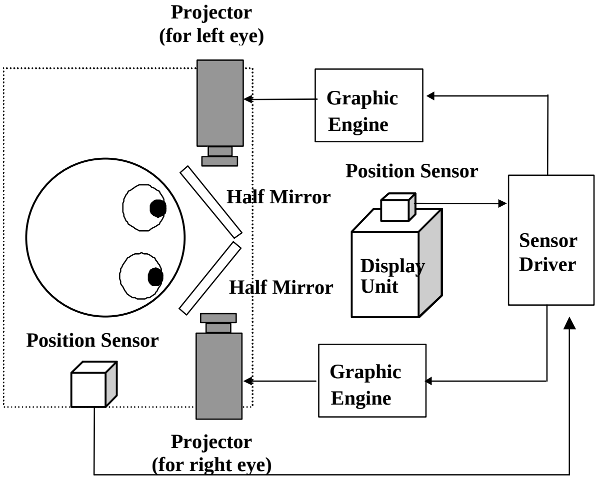


Fig. 8 Principle of a Head-Mounted Projector (HMP)

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. C-mount camera lens (12.5[mm] focal length) projects the image with wide angle (horizonal:60[deg]). Eye relief is long (70 [mm]) enough to wear HMP with glasses.

The weight is 1650[g]. Thus, the weight is balanced with counter weight and constant force springs using wire-pulley mechanism.

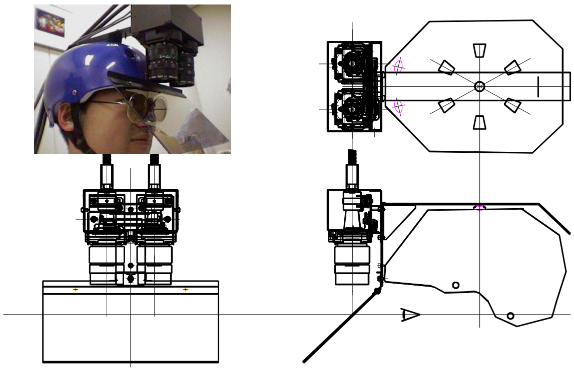


Fig. 9 HMP model-2

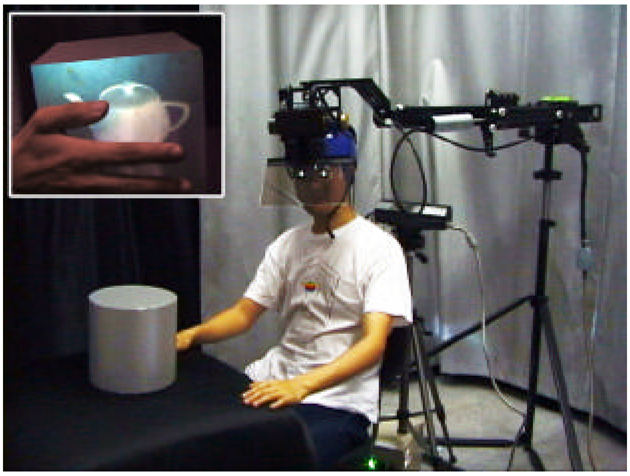


Fig. 10 HMP model-2 with mechanical 6 D.O.F. position sensor and projected image

Fig. 10 shows an example of an image projected on a screen covered with retroreflective material with the accurate occlusion relationships. The image can be clearly observed under the room light (about 200[lx]). This projection method does not require to be in 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 important as displaying a virtual object.

Most of force displays consist of mechanical devices, which occlude virtual objects. Actually, this occlusion problem occurs nearby the target object, where an operator have to observe more clearly. Moreover the haptic device occlude not only the virtual object but also a background real environment.

By using HMD, the operator can observe the virtual object clearly. However he/she can't observe his/her real hand. This problem obstruct sensation of presence, too.

To solve these problem, 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 masking object virtually transparent. Moreover, to project stereoscopic image, the observer looks at the masking object more transparent.[21]

Optical Camouflage can apply for a real scene.

In the case of a real scene, a photograph of a real scene is taken from operator's viewpoint, and this photograph is projected on the exactly the same place as the original. An example of Optical Camouflage for a real scene is shown in Fig. 12. It will requires some kinds of Image-based rendering techniques, to apply HMP-based Optical Camouflage for a real scene.

An example of Optical Camouflage for a real scene is shown in Fig. 12.

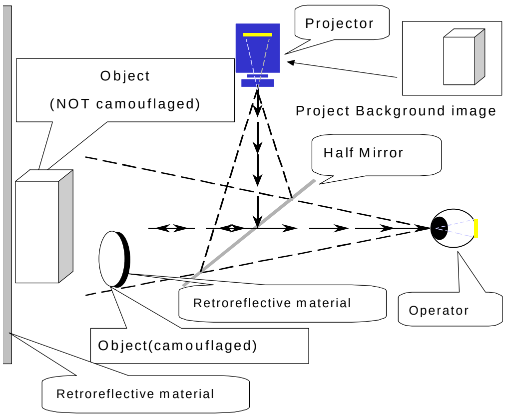


Fig. 11 Implementation of Optical Camouflage

Fig. 12 Example of Optical Camouflage for a real scene

In this case, a brick covered with retroreflector hides a bookshelf. To project the background image onto the brick, an observer can observe that the brick become transparent. Actually, the background image was projected not only on the brick but also the other place. However, the image projected on all place except on the brick is too dark to perceive. Thus, only the brick looks like transparent.

4.2 Prototype Visuo-Haptic Display

We applied Optical Camouflage to a visuo-haptic display. Fig. 13 shows a principle of an object-oriented visuo-haptic display.

We used HMP model2 for a visual display part and PHANToM Desktop for a haptic display part. The haptic display was covered with retroreflector.

PC-based control unit and graphic engine get both an operator’s hand position and his/her head position.

As the result, virtual environment projected from the HMP onto both the haptic display and retroreflective screen. On the other hand, the haptic display is controlled simultaneously.

Hence, the observer can touch the virtual object such as it is seen.

Fig. 14 shows the 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 transparent perfectly. The shape of the haptic display are observed clearly. Nevertheless, it looks like very low refractive index glasswork, which is enough to observe behind image.

This configuration has one difficulty. The operator does not allow to touch the back of the virtual object with collect occlusion relationship. Then we plane to develop a object-oriented visuo-haptic display.

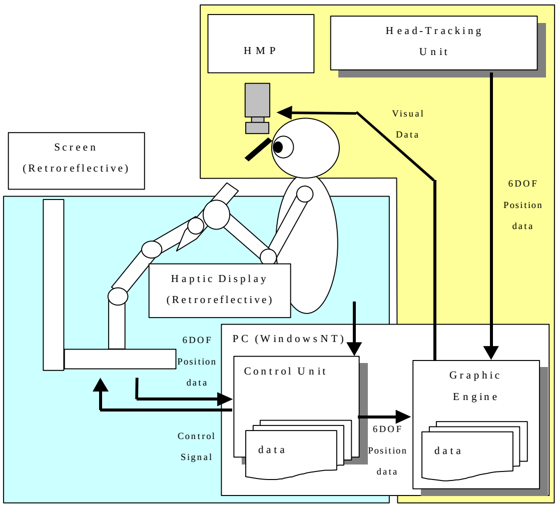


Fig. 13 Principle of a visuo-haptic display using Head-Mounted Projector

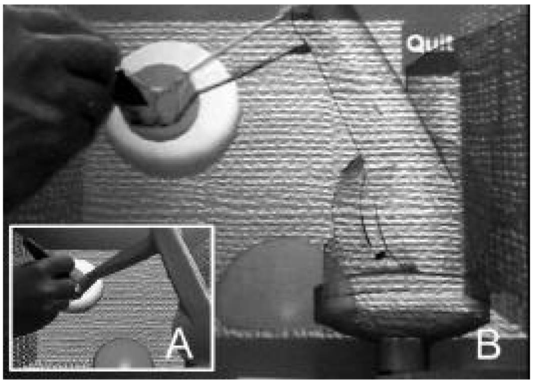


Fig. 14 Optical camouflaged PHANToM, A: Before Camouflaged, B: After Camouflaged

5. Conclusion

In this paper, we described that the 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 HMP was developed based on the design procedure.

The user can observe stereoscopic images with an correct occlusion relationship between the virtual and the real environment. In addition, the image on the retroreflective screen is bright enough to observe virtual objects under 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.

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

We succeeded in camouflaging force display which obstruct visual images. Such viewer is able to observe as if the force display is transparent. Hence the viewer can observe

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

6. Acknowledgement

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