

## **Enhancing Virtual Environment Interaction Using a Head Mounted Projection Display (HMPD)**

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### **ABSTRACT**

Interacting with a Virtual Environment (VE) generally requires the user to correctly perceive the relative position and orientation of virtual objects. For some VE applications, such as near-field mixed reality, the user may also need to accurately judge the position of the virtual object relative to that of a real object, for example, the user's hand. This is difficult, since VEs generally only provide a subset of the cues experienced in the real world. Complicating matters further, VEs presented by currently available displays are often inaccurate or may be distorted due to technological limitations.

One recent development is the Head Mounted Projection Display (HMPD). It has the potential to address this interaction problem. The HMPD uses a projection lens and retro-reflective material instead of the eyepiece found in a typical head mounted display. This solves several problems in mixed reality simultaneously. Specifically, it allows for proper occlusion, for correction of optical distortion, and for images to be retro-reflected off curved surfaces. HMPD technology has been researched for use in medical visualization and collaborative virtual environment applications (Rolland, Meyer, Davis, Hamza-Lup, & Norfleet, 2002; Hua, Gao, & Rolland, 2002).

The unique combination of visual cues provided by the HMPD technology can potentially allow one to effectively reach, select, manipulate, and release virtual cockpit controls, specifically, buttons, dials, and switches in a direct and natural manner. We present a test bed design and experimental designs to explore this feasibility. We provide basic task measures and expected results for interaction with these virtual objects. Finally we provide preliminary data for accuracy and precision of one key measure for object manipulation, the user's depth perception of virtual and real objects in relation to each other. The technology has the potential to replace the physical mockup of a cockpit with its virtual counterpart, making training systems more portable, deployable, and reconfigurable.

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### BACKGROUND

The Navy training community, as with other industries, has explored the potentials for portability, deployability, and reconfigurability of Virtual Environment (VE) as solutions for many applications. Recently, the Navy fielded a virtual reality training system, Virtual Environment Submarine – VESUB2000. The entire training system is not much larger than a mockup of the bridge the conning officer stands in when commanding the submarine. Shrinking similar trainers to deployable size, however, remains a challenge mainly due to the necessity of physical mockups such as the vehicle cockpits.

Shrinking the cockpit to computer bits and bytes means having to interact with virtual objects, specifically, reaching, selecting, manipulating, and releasing virtual buttons, dials, and switches in a direct and natural manner. Herein lies the research challenge. Visual displays presenting two-dimensional images cannot provide perfectly faithful three-dimensional views (Wann, Rushton, & MonWilliams, 1995). Haptic displays (for the sense of touch) are usually difficult to implement due to the requirements of force feedback and can be even bulkier than the physical cockpit mockup itself. Recent development of a new head mounted display (Hua, Girardot, Gao, & Rolland, 2000) may offer the needed edge to tackle the problem with direct, natural manipulation of virtual objects. A virtual environment (VE) that supports such interaction would be a significant step toward eliminating bulky, physical mockups. The purpose of this paper is to describe a VE test bed supporting such a near-field egocentric task. Experimental design, task-based measures, expected results, and preliminary results are presented.

### Visual Sensory Modality

Visual parameters typically considered in training simulations include acuity (unmatched by display resolution), instantaneous field of vision (again unmatched by display field of view), aerial and linear perspective, size and height, texture and gradient, lighting, shade, shadow, and motion parallax. Besides these, additional visual cues are essential for interacting with objects in the near-field. These additional cues include occlusion, vergence, accommodation, depth of field, and stereopsis and are briefly reviewed below.

Occlusion refers to the interposition of one object on another and is a relatively trivial cue to provide for immersive applications. For mixed reality, however, this generally requires precise, real-time tracking of objects and considerable computational power for correct presentation. It is an important (and sometimes the only) depth cue available in a visual scene.

Convergence, divergence, conjugate, and, collectively, vergence, refer to the inward, outward, parallel, and all rotation of the eyes, respectively. Vergence has been shown to provide depth cues (Ellis & Menges, 1997).

Accommodation refers to the focusing of the eye. Vergence and accommodation are neurally cross-linked, i.e., each affects the other. Accommodation producing vergence eye movements is termed accommodation vergence. Similarly, vergence producing accommodation is termed vergence accommodation (Wann and Mon-Williams, 2002). Simulations tend to decouple this cross-link producing unnatural visual conditions.

Closely related to accommodation is depth of field, which is the range where objects are in focus instantaneously. As an example, for a nominal 4

millimeter pupil and an object 1.0 meter away, the depth of field is from 0.94 to 1.06 meters. Tolerance for blur considerably extends this apparent depth of field.

Stereopsis refers to depth perception arising from lateral retinal image disparity. Lateral separation of the eyes provides each with a different perspective, and therefore, disparate images that are psychologically fused together, contributing to depth perception, particularly in the near-field.

### **Other Sensory Modalities and Cross-Modal Interactions**

Other modalities besides vision, specifically, audition, haptics, and proprioception, are also salient to interaction in near-field mixed reality. Auditory cues enhance awareness of the VE and are especially useful for collision or tactile cueing (Shilling & Shinn-Cunningham, 2002), e.g., virtual button pushes. Haptics include sensations arising from stimulation of receptors in the skin and associated tissues (Vince, 1995). While vision dominates spatial tasks, haptics can substitute or provide redundant information (Boff & Lincoln, 1988) that improves overall perception or task performance (Popescu, Burdea, & Trefftz, 2002). Mon-Williams & Wann (1998) also found that when visual background is lacking, haptics could be more dominant. Finally, proprioception is the sense of body position and movement. Proprioception uses receptors within joints, muscles and deep tissues (Vince, 1995). Proprioception can also dominate in spatial tasks, when vision is lacking (Boff & Lincoln, 1988).

Both vision and audition provide spatiotemporal information. The overlap results in constructive redundancy if synchronized and augments perception in both senses. Similarly for the haptics-visual pair, Biocca, Kim, and Choi (2004) demonstrated that haptic sensation is perceived when there is none displayed if the visual sensation is convincing. Such perceptual illusion is termed synesthesia. Gross (2004) also demonstrated instances where substituting cues from one modality for another that is absent improves perception of affordances and, therefore, task performance.

The above findings provide evidence for the effectiveness of VEs that incorporate multi-modal displays, specifically, vision, audition, haptics, and proprioception, to support direct, natural manipulation of objects. Moreover, there is a multidimensional trading space for substituting or complementing one modality with another when certain cues are absent or

lacking. The test bed and experiments described below make full use of potential combinations of the sensory modalities discussed above.

### **Mixed reality Display Technology**

Display technologies relevant to sensory cues discussed above were considered for this test bed and are described below.

Optical See-Through HMD (OSTHMD) presents an unhindered view of the real world, and therefore provides for perfectly synchronized information between visual and proprioception information. One drawback of the OSTHMD is that the virtual image is simply superimposed onto the real image, not fused correctly to properly present occlusion cues in mixed reality.

Video See-Through HMD (VSTHMD) can guarantee registration of the real and virtual scenes and can provide for proper occlusion in mixed reality. However, this image fusing process requires extensive computational resources. Therefore, a finite delay exists causing a mismatch between vision and proprioception.

Computer Animated Virtual Environments (CAVEs) and virtual workbenches are projection type systems. The users generally wear stereoscopic glasses, called shutters, which are synchronized with the projector to alternately open and close when the proper left or right image is displayed and shut off. On the negative side, the image is generally only geometrically correct for one user. Keystoning, a visual distortion as a consequence of off-axis projection, is also frequently observed. Additionally, these displays cause contradiction in accommodation, convergence, and perceived depth because the image is on the projection screen, where the eyes are focusing, but the perceived depth and convergence of virtual objects could be at other points.

Autostereoscopic displays can produce a stereo effect without the need for glasses. For these displays, however, the user's head is not tracked so geometric accuracy of the images is not guaranteed.

Rolland, Krueger, & Goon (2000) described a prototype multiplanar volumetric display that can suppress accommodation and convergence conflicts. This has the potential for applications requiring visualization of the near- and far-field simultaneously. However, the system is not yet available for experimentation.

A Virtual Retinal Display (VRD), or Retinal Scanning Display (RSD), uses low-power lasers or LEDs (Light Emitting Diodes) and microelectro-mechanical mirrors to scan the image directly on the human retina. These displays are very lightweight and can be very bright. However, as with OSTHMD, correct occlusion in mixed reality is still a problem that is not addressed by VRD/SRD.

A Head Mounted Projection Display (HMPD) is similar to an OSTHMD except that the image is projected forward onto a screen and retro-reflected back to the user's eyes. Fundamentally, it possesses a unique combination of features that overcomes all shortfalls discussed above and addresses all salient visual cues discussed in the previous sections (Hua, Girardot, Gao, & Rolland, 2000). Some of the key HMPD features are:

- 1) Correct occlusion – projecting the image allows for correct occlusion of the virtual object by the real object, like the user's hand. As the user reaches out to select or grab a virtual object, the hand instantaneously and correctly occludes that object.
- 2) Image plane position independent of screen position – the image plane can be set to any depth near the retro-reflective screen, in front of, behind, or on it. Incidentally, if the image plane is between the user and the screen, the image is actually an optically real image, as if an invisible screen is manifested in mid-air onto which the image is projected.
- 3) Correction of optical distortion – the HMPD can be designed to minimize optical distortion. Correcting for distortion with accuracy and speed has always been a challenge with software (and firmware) for conventional HMDs.
- 4) Absence of keystoneing – Projection displays generally suffer from keystoneing, a consequence of off-axis projection with respect to a user's eye points.
- 5) Real world view synchronized with proprioception – as with OSTHMD, the HMPD presents an unhindered and instantaneous view of the world and thus provides for perfect synchronization with proprioception.

#### **Display Technology vs. Display Capabilities for Direct Object Manipulation**

Direct manipulation of an object requires precise knowledge of its location - height, width, and depth. Of these, the most difficult to display correctly and to calibrate accurately is depth. Cutting and Vishton

(1995) suggest that the main cues pertaining to depth perception in personal space include occlusion, stereopsis, motion perspective, relative size, accommodation, and vergence. Of these, they suggest that occlusion, closer objects blocking farther ones, is the most important. It is the most effective depth cue for objects at any distance. Ellis & Menges (1997) found that task errors can stem from missing or incorrect occlusion cues.

Stereopsis is the second most important cue. Depth can be perceived through stereopsis without accommodation and vergence, as is the case with autostereograms, e.g., random-dot stereograms (Liu, Stark, & Hirose, 1991). Motion perspective and relative size are adequately provided by computer graphics software, and therefore, will not be discussed in detail. Finally, correct accommodation and convergence is important not only for depth perception but also for reducing visual load (Ellis & Menges., 1997; Wann & Mon-Williams, 2002).

The authors of this paper suggest that correction of optical distortion, synchronization of visual and proprioception modalities, and support for multiple users are also salient to applications of direct object manipulation. Robinett and Holloway (1995) claim that one of the most common visual errors in VE is ignoring the distortion caused by the optics. Regarding vision and proprioception synchronization, eye-hand coordination is essential for reaching, grabbing, and manipulating objects. Having instantaneous visual and proprioception cues eliminates dissociation of seen and physical hand displacement, which could induce sensory rearrangement (DiZio & Lackner, 2002; Biocca & Rolland, 1998). Similarly, having a direct, faithful view of the hand could reinforce and enhance both modalities as Popescu et al. (2002) found for vision and proprioception. Finally, the authors of this paper note that support for multiple users is a feature for a wide variety of applications, such as team training.

In summary, the visual display capabilities most salient to near-field depth perception and natural, direct manipulation of virtual objects are listed in the columns of Table 1. These include correct occlusion (O), Stereoscopic (S), Correct Accommodation (A), Correct Convergence (C), Zero Distortion (D), Proprioception and Visual Synchronization (P), and Multi-User Support (M). Based on the discussions above, the authors suggest that the HMPD technology can provide all these cues simultaneously, and with the high perceptual fidelity necessary for near-field object manipulation.

**Table 1.** Display Technology and Capabilities Mapping for Near-field Object Manipulation

3D Display Technology	Display Capabilities						
	O	S	A	C	D	P	M
OSTHMD		X	X	X		X	X
VSTHMD	X	X					X
CAVE / Virtual WB	X	X				X	
Autostereoscopy	X	X	X	X		X	
Volumetric Display	?	X	X	X	?	X	X
VRD/SRD		?	X	X	?	X	X
HMPD	X	X	X	X	X	X	X

## THE RESEARCH

The literature abounds with the advantages of manipulation of real objects, instead of virtual objects, in mixed reality (Biocca and Rolland, 1998; Lehner & DeFanti, 1997; Hua et al., 2002; Lok, Naik, Whitton, & Brooks, 2003; Schiefele, 2000). The user has a direct view of the hands and the objects (e.g., the yoke, flight stick, or cockpit control panels, for manual interaction). It is convenient at this point to introduce an acronym, RR, for Real hand manipulating Real objects. The equipment fidelity, the accuracy of the visual cues, and the empirical evidence of task efficiencies for RR are indisputable compared with other techniques that will be discussed below. However, the physical environment, as discussed previously, requires a large footprint to house all the objects the user must directly and manually interact with in personal space.

The literature also reveals evidence that a purely virtual environment can provide for effective interaction in certain applications (Beier, 2000; Von Wiegand, Schloerb, & Sachtler, 1999; Latham, 1998; Lok et al. (2003); Schiefele, 2000). The authors introduce another acronym, VV, for Virtual hand manipulating Virtual objects. For interaction with virtual controls such as those in a vehicle cockpit, it is clear that haptic displays are necessary to confirm spatial layout (Schiefele, 2000). Even with haptics, efficiency of VV is still far from the ideal performance of manipulating

real objects in RR. Haptic displays, obviously, add more footprint as well as rigidity to the VE.

Finally, the authors introduce the acronym RV, for Real hand manipulating Virtual objects. Research in this area has mostly focused on depth perception of one object in relation to another (Rolland, Gibson, & Ariely, 1995; Ellis & Menges, 1997). The only successful interactive applications of RV is through the use of indirect or unnatural manipulation of objects, for example using a stylus or gross gesture recognition of the hand (Kruiger, Bohn, Frohlich, Schuth, Strauss, Wesche., 1995; Leibe, Starner, Ribarski, Wartell, Krum, & Singletary, 2000; Inami, Kawakami, Sekiguchi, Yanagida, Maeda, & Tachi, 2000).

## Direct and Natural Manipulation of Virtual Objects

Although no research has been done for direct, natural manipulation of virtual objects, the authors suggest that successful research in adjacent areas mentioned above (RR, VV, indirect interaction, and depth perception) indicates that RV may be feasible, given the right visual cues and other sensory modalities. This is the motivation for the research and the basis for the hypothesis and experiments described next.

## Research Questions and Hypotheses

The authors propose two research questions and suggest an initial hypothesis for each. First, does mixed reality using HMPD provide for adequate depth perception that would facilitate direct manipulation of virtual objects? Previous work shows that depth perception is adequate, but only for a perfect laboratory setup, such as an optical bench, and without proprioception cues (Rolland, 2002b). With a HMPD and with proprioception cues, the authors hypothesize that given a high visual fidelity and binocular condition, the user will be able to perceive depth with millimeter accuracy for both real objects, such as the hands, and virtual objects, such as buttons.

The second research question is more practical. How accurately and how quickly can the tasks be completed using this mixed reality environment compared with the those from the real environment? Previous work shows that spatial perception accuracy is in the millimeter range (Ellis & Menges, 1997, Rolland et al., 2002b). Typical cockpit controls, e.g., buttons, are at least a half-inch or tens of millimeters in size. It seems spatial perception error in virtual environments can be a few times smaller than the typical size of the objects to be manipulated. Therefore, the authors of this paper hypothesize that manipulating virtual objects can be as

effective as manipulating real objects, given the proper visual cue fidelity synchronized with proprioception and audition.

### **Test Bed Design**

Image generation hardware and software for the test bed includes a computer PC with Windows XP and a Matrox 256MB dual output graphics card. Modeling software used is Multigen-Paradigm Creator. Simulation software used is Multigen-Paradigm Vega, which can generate disparate binocular views and provides for easy adjustment of field of view, aspect ratio, interpupil distance (IPD), and perspective to match those of the visual display and the test subject.

Visual displays for the test bed include an nVision Hi-resolution Datavisor optical see-through HMD and a HMPD. The optical see-through HMD and the HMPD also have adjustments for head size and position and IPD to match those of each test subject.

An Intersense 600 system is used to track the head and the hand. This is a hybrid acoustics- and accelerometer-based system. The sonic discs (acoustics) are used to compensate for drift and provide absolute distance information. The inertial cube provides relative positional distance and angular rotation information. The same system is used for the head and the hand so that any error or delay introduced to the head is also presented with the same magnitude and direction to the hand offsetting each other.

A Cyberglove with 18 sensors is used to track the finger positions on the hand. A Pinch Glove is used to indicate selection of virtual objects.

A number of real and virtual buttons, dials, and switches are used. Buttons include push buttons, radio buttons, and push buttons secured by a cover. Switches include those with two and three positions. Dials include step-free types, step-free with on-off button, multiple-step, pull-push functionality, and dials with inner-outer rings. These are the types of controls typically found in flight cockpits (Schiefele, 2000).

### **Experiment Design 1. Fundamental Mixed reality Depth Perception**

The task for Experiment 1 is to match the depth of one object with that of a second using the method of adjustment. The independent variables are:

1) three levels of VE: RR, RV, and VV;

- 2) two levels of visual cues: correct accommodation and convergence settings and nominal accommodation and convergence settings; and
- 3) two levels of kinesthetic proprioception cue: absence and presence.

The first independent variable, VE, is controlled by using a HMPD and an optical see-through HMD, both of which can provide for simultaneous views of virtual and real objects. Both displays also have adjustments to control the second set of independent variables -- accommodation and convergence. Finally, for the third independent variable, the subject uses a dial to indirectly move the object for the "proprioception-absent" condition and uses the hand directly on the object for the "proprioception-present" condition.

The dependent measures for this experiment are precision and accuracy of depth perception, i.e., absolute error and resolution of final separation between the two objects in the sagittal plane.

This first experiment partially duplicates previous work by Rolland et al. (2002b), but using the HMPD instead of an optical bench. Additionally, the experiment controls accommodation, convergence, and proprioception cues to test the effect of each on precision and accuracy of depth perception. The experiment quantifies depth perception for all three conditions: RR (Real Object next to Real Object), RV (Real Object next to Virtual Object), and VV (Virtual Object next to Virtual Object).

### **Experiment Design 2. Object Interaction**

Tasks for Experiment 2 are localization, selection, manipulation, and release of objects. Independent variables are occlusion, visual lighting indication, audio, and haptics. Each variable has two levels -- presence or absence. Dependent measures are spatial position precision (p) and accuracy (a), time to complete (t), and error rate (e).

For the first task, the subject moves the hand to the object indicated by the computer or the researcher at the cue of a sound. In addition to the cues of accommodation, convergence, and proprioception in experiment 1, the subject gets the cue of occlusion. Spatial precision and accuracy, as well as completion time are measured. This is done for all three cases - RR, RV, and VV. This part of the experiment allows one to quantify the effect on performance provided by the cue of correct occlusion.

For the second task, the subject pinches the glove when he/she feels that he/she has positioned the index finger on the object. The object, if correctly selected, lights up. This is the only feedback received in addition to the previous cues (accommodation, convergence, proprioception, and occlusion). Spatial precision and accuracy, error rate, and time to complete are measured. This part of the experiment allows one to quantify the effect of timely visual feedback on the performance of the simple task of selecting a button, dial, or switch. Comparisons are also made between RR, RV, and VV conditions.

For the third task, the subject manipulates the object with an additional cue, diotic audio feedback. For the button, the subject pushes, i.e., moves the finger in the sagittal plane. For the switch, the subject flips, i.e., moves the finger in the frontal-parallel plane. For the dial, the subject turns, i.e., rotates the finger and thumb in the frontal-parallel plane. Measures are time to complete and error rate. Comparisons are also made between RR, RV, and VV conditions.

For the final task, the subject releases the object after manipulating it. This time, simple touch feedback in the form of a plastic panel is added. Measures are time to complete and error rate. As before, comparisons are made between RR, RV, and VV conditions.

### **EXPECTED RESULTS**

For the first experiment, pilot (test) runs were conducted in June 2004 to fine-tune the test bed, finalize the experimental design, and determine the number of subjects needed. Preliminary results are similar to that shown from previous research with optimal accommodation and convergence settings. The addition of the proprioception cues is expected to improve precision of depth perception even further. Therefore, the results are expected to provide strong evidence that visual fidelity synchronized with proprioception cues is adequate for interaction with virtual objects. The actual formal depth perception experiment is currently ongoing.

For the second experiment, it is expected that manipulating virtual objects will take slightly longer to complete, but that errors made will be comparable to that for manipulating real objects. This is based partly on empirical evidence of previous research and predictive models.

Empirically, Schiefele (2000) found that 5.5 seconds, on average, is required to manipulate virtual cockpit controls (using the VV technique but without optimal

visual perceptual fidelity). Only 1.5 seconds is required for real controls (RR technique). Schiefele added simple touch haptics to the virtual condition (not quite RV technique but a step in that direction) and reduced the interaction time to 3.5 seconds.

Analytically, the authors calculated task completion time for manipulating a button using the Model Human Processor (MHP, Card, Moran, & Newell, 1983). This MHP provides for prediction of action time relatively accurately, especially for simple tasks. The model takes into account average perceptual processing time,  $T_p$ , of about 100 ms, cognitive processing time,  $T_c$ , of about 70 ms, and motor processing time,  $T_m$ , of about 70 ms. Conservatively, simple button pushing action time was calculated to be on the order of 2.0 seconds for the RR condition, 2.4 seconds for the RV condition, and 3.0 seconds for the VV condition. These estimates show a significant improvement of RV over VV with RV approaching that of the ideal condition of RR.

### **Implications**

Controls, such as those on a typical cockpit panel, if ergonomically designed, are at least 0.5 inches apart and in length, width, or height (Boff & Lincoln, 1988). The pilot experiment conducted in this effort showed that accuracy and depth perception of virtual objects is well within this parameter. The formal experiment, currently ongoing, is expected to show similar results, but with greater reliability. One could conclude that a mixed reality virtual environment can be designed with adequate physical fidelity for manual interaction with virtual cockpit controls.

Additionally, aside from the yoke, pedals, levers, or flight stick, all other controls in a typical vehicle cockpit are buttons, knobs or switches. Experiment 2 is expected to show that one can effectively manipulate similar controls that are virtual. If this is the case, the hundreds of real buttons, knobs, and switches typically found in a flight simulation cockpit can be replaced with their virtual counterparts without significant reduction in perceptual fidelity. The physical cockpit mockup in current flight trainers could potentially be reduced to a seat with levers, pedals, and yoke or flight stick making flight simulation trainers significantly more portable, deployable and reconfigurable. Incidentally, the test bed described above has been integrated into a research vehicle simulation, Virtual Environment Landing Craft, Air Cushioned (VELCAC), for the purposes of demonstrating these techniques.

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