Design and Evaluation of a Hybrid Display System for Motion-Following Tasks

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Abstract. Hybrid display systems are those that combine different types of displays to exploit the complementary characteristics of the constituent display systems. In this paper, we introduce a hybrid system that combines a stereoscopic optical see-through head-mounted display (HMD) and a large projection display for an application in a multi-user ship painting training scenario. The proposed hybrid system's projection display provides a large FOV and a physical metaphor to the ship surface with natural depth perception, while the HMD provides personal and unoccluded display of the motion training guides. To quantify its effectiveness, we conducted a human subject experiment, comparing the subject's motion following task performance among three different display systems: large projection display, head-mounted display, and hybrid. The preliminary results obtained from the experiment has shown that given the same FOV, the hybrid system performed, despite problems with registration between the real and virtual worlds, up to par with the head-mounted display, and better than the projection display. Thus, it is expected that the hybrid display will result in higher task performance with the larger FOV factor available.

1 Introduction

In virtual or mixed reality systems, usually visual display systems of a single type are combined to achieve certain functionality, for example, a large FOV or stereoscopy [1, 3]. On the other hand, hybrid display systems are those that combine different types of displays, equally to meet certain visual needs, but by exploiting the complementary characteristics of the constituent display systems. For example, Ilie et al. introduced a hybrid display system that consisted of a high-resolution stereoscopic head-mounted display (HMD) and a low resolution wide FOV projector display to provide an effective imagery to surgical trainees who needed to be spatially aware of one's surroundings, yet be able to concentrate on a central object [4].

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Another avenue to leverage on the merits of the head-mounted display and wide FOV projection display is in a multi-user motion training scenario (note that in [4], although the application domain was also a training system, the training occurred through passive first-person viewpoint visualization). One particular application is the training for spray painting of ships. Spray painting of ships requires careful timing and following regular motion profiles to ensure uniform paint thickness on the surface. We can envision a VR-based training system in which only a large projection display is used with its zero parallax plane corresponding to the ship surface. In addition, with stereoscopic support (e.g. shutter glass or light polarization), one can simulate the required close-range 3D motion profiles to train a user. The problem is that it is difficult to display the motion training guide because of the occlusion by the hands on which the virtual spray gun must be rendered (and overlaid). The same system can be realized using an HMD, however, it is expected that the use of a large projection would be better because of the large FOV, and the natural physical metaphor to the ship surface (and depth perception). A hybrid display, e.g. HMD + projection display, offers a solution; the projection still provides the large FOV and physical metaphor, and the HMD provides unoccluded motion guides for the hands. In addition, the hybrid system allows multiple users to train at the same time.

In this paper, we present a hybrid system that combines a large projection display and an optical see-through HMD to be used as a display system for training ship spray-painting. To quantify its effectiveness, we conducted a human subject experiment, comparing the subject's motion-following task performance among three different display systems: (large) projection only, head-mounted display only, and hybrid. This paper is organized as follows. In the next section, we review the work related to the hybrid visual display systems. Section 3 describes the details of our hybrid display system, and Section 4 steps through the human subject experiment and the derived results. Finally, we conclude the paper with an executive summary and directions for future research.

2 Related Work

The concept of the hybrid display was first introduced in 1991 by Feiner and Shamash who combined an HMD and a flat panel display to provide personal context information [2]. Others have attempted to mix different types of displays as well. Researchers from the Fraunhofer Institute developed a visualization system that combined a central autostereoscopic 3D display with surrounding 2D displays [7]. However, in general, not much work has been published regarding system designs nor usability of hybrid display systems.

Our idea of using the projection surface metaphorically mapped to a virtual object (in this case, the painted ship surface) is similar to the work on life-sized projector-based dioramas by Low et al. [6]. Their work aimed at creating life-sized immersive virtual environments by projecting on physical objects that roughly approximated the geometry of the objects it was to represent.

An HMD with a wide field of view is hard to come by because of the technical (e.g. wide angle folding optics), economical (e.g. high resolution) and ergonomic (e.g. light weight) difficulties. Slater and Usoh simulated a wider FOV by rendering the foveal region normally and by compressing more of the scene into the outer regions of the display area [8]. Yang and Kim also have shown that the effective FOV could potentially be increased up to twice the physical FOV by scaling down the imagery without significant distortion in depth perception when multimodal interaction is used [11].

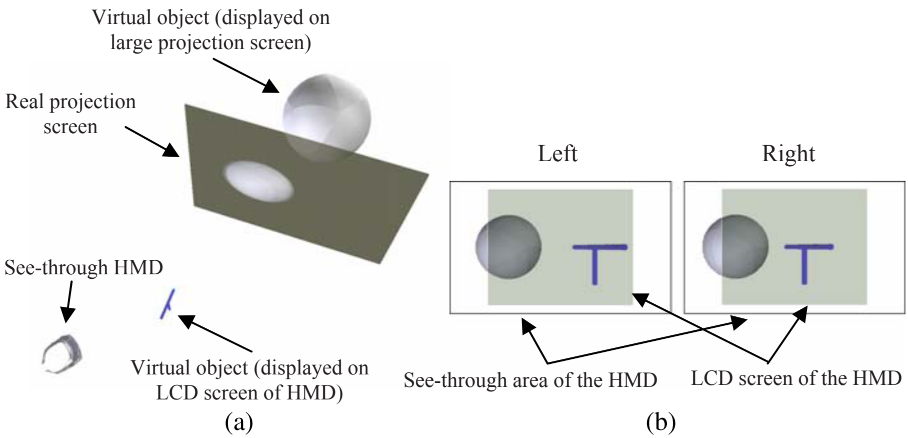


Fig. 1. An illustration of combining the images displayed on the projector screen and displayed on the LCD screen of the see-through HMD. (a) An example of the configuration using both the large screen and the see-through HMD. (b) Combined stereoscopic image pair shown through the see-through HMD.

3 Implementation of a Hybrid Display System

In this section, we describe implementation details of our hybrid display system that consists of a rear-projected large display and a see-through HMD. The large display had the screen size of 140cm × 105cm, and used two projectors for passive stereoscopy with circular polarized light filters. Each projector supported a resolution of 1280 pixels × 1024 pixels. The optical see-through HMD (called Deocom SX-500) had a resolution of 1280 pixels × 1024 pixels, an aspect ratio of 5:4, and a vertical FOV of 27.4°. The circular polarized light filters were also attached to the HMD, so users could see both the stereoscopic image displayed on the large projection screen and that displayed on the LCD screen of the HMD at the same time (see Figure 1).

The projection models for the large display and for the HMD were different from each other in order to correctly register images on the projection screen and on the LCD screen of the HMD. While the standard perspective (on-axis) projection model was used for the HMD, an off-axis (head-coupled) perspective projection model was used for the large display. The viewing frustums for the large display and for the HMD were made to be seamlessly combined, by adjusting the near and far clipping planes for each display For head tracking, the Intersense IS-900 VE head tracker was attached to the HMD, and the offset to the center position between the left and right eyes from the tracker sensor was estimated with the 3D CAD model of the HMD provided by the HMD manufacturer. Images for the large display and for the HMD were generated from two separate PCs, which were connected to same tracker sever through the VR Peripheral Network [9].

Although each parameter for the projection models was carefully and precisely measured, it was not enough to correctly register images on the projection screen and on the LCD screen of the HMD. It was because the IPD of the HMD (which was fixed at 6.5cm) could be different from those of users. In order to match the distance between the centers of two images for left and right eyes with user's IPD (which was measured with a pupilometer), we performed a simple calibration procedure. In the procedure, the user was required to adjust the viewport positions (the first two parameters of OpenGL glViewport() function) of stereo pair images rendered with her/his IPD. The detailed procedure followed the steps below:

- *Step 1*: Display two identical reference left eye images (e.g. blue painting gun) each on the projection screen and on the see-through HMD screen.
- *Step 2*: For a given user, while wearing the see-through HMD, adjust the viewport parameters for the HMD using the joy stick on the wand until the two images are reasonably fused and registered.
- *Step 3*: Repeat Steps 1 and 2 for the right eye.

The hybrid display system was applied to a simple painting-training application using the Ghost metaphor [10]. In the application, users could paint on a virtual object (displayed on the large projection screen at a distance of 2m) in a given pattern with a virtual blue painting gun controlled by (and drawn at the position of) a wand, while following the guided motion of a virtual yellow painting gun. An example is shown in Figure 3.

4 Experiment

4.1 Independent and Dependent Variables

The independent and dependent variables considered in the experiment are shown in Tables 1 and 2, respectively. We compared three display types: using a large display only (PROJECTOR), using a see-through HMD only (HMD), and using both a large display and a see-through HMD (HYBRID). Each display type could be simply set up by adjusting the near and far clipping planes for each display system, because the positions of target objects were fixed and the virtual painting gun (or user's hands) and the viewpoints could be located only in the given range (note that the guide painting gun moved through the predefined paths). Since the paths of the guide motion might have an effect on the dependent variables, the different types of the guide motion (or painting pattern) were also considered as an independent variable. The FOV of the see-through area was set approximately equal to that of the HMD to make the experiment conditions the same. In other words, FOV was not a factor in this experiment.

4.2 User Tasks

In the experiment, each participant carried out six types of the painting task: three types for training and three types for actual trials. The task types are described below:

Table 1. The independent variables considered in the experiment

Display Type	
Level	Description
PROJECTOR	All objects are displayed only on the large screen.
HMD	All objects are displayed only on the LCD screen of the see-through HMD.
HYBRID	Target objects are displayed on the large screen, and the painting guns (including the guide gun) are displayed on the LCD screen of the see-through HMD.
Guide Motion (or Painting Pattern) Type	
Level	Description
HORIZONTAL	The guide painting gun moves mainly in a horizontal direction (The painting pattern is horizontal).
VERTICAL	The guide painting gun moves mainly in a vertical direction (The painting pattern is vertical).
CIRCULAR	The guide painting gun moves through a circular path (The painting pattern is circular).

Table 2. The dependent variables considered in the experiment

Name	Description
PD	The average position difference between the user and the guide motions.
OD	The average orientation (represented by unit quaternions) difference between the user and the guide motions.
PPD	The average distance between the given painting pattern and the user painting result.

- *Training Task 1*: Spraying red paint freely on a gray square plane (side length = 90cm) located about 2m ahead (see Figure 2).
- *Training Task 2*: Spraying red paint on the gray plane in a "horizontal" pattern while following the motion of a yellow guide painting gun. The guide gun moved in horizontal direction only for 10 seconds, and its orientation was not changed (see Figure 3).
- *Training Task 3*: Spraying red paint on the gray plane in a "vertical" pattern while following the guide motion. The guide gun moved in vertical direction only for 10 seconds, and its orientation was not changed.
- *Actual Task 1 (HORIZONTAL)*: Spraying red paint on a gray sphere (radius = 30cm) located about 2m ahead, while following the motion of the yellow guide painting gun for 10 seconds. The painting pattern was "horizontal," but the orientation of the guide gun, as well as its position, was changed (see Figure 4a).
- *Actual Task 2 (VERTICAL)*: Spraying red paint on the gray sphere, while following the guide motion for 10 seconds. The painting pattern was "vertical," but the orientation of the guide gun, as well as its position, was changed (see Figure 4b).
- *Actual Task 3 (CIRCULAR)*: Spraying red paint on the gray sphere, while following the guide motion for 30 seconds. The painting pattern was "circular," but the orientation of the guide gun, as well as its position, was changed (see Figure 4c).

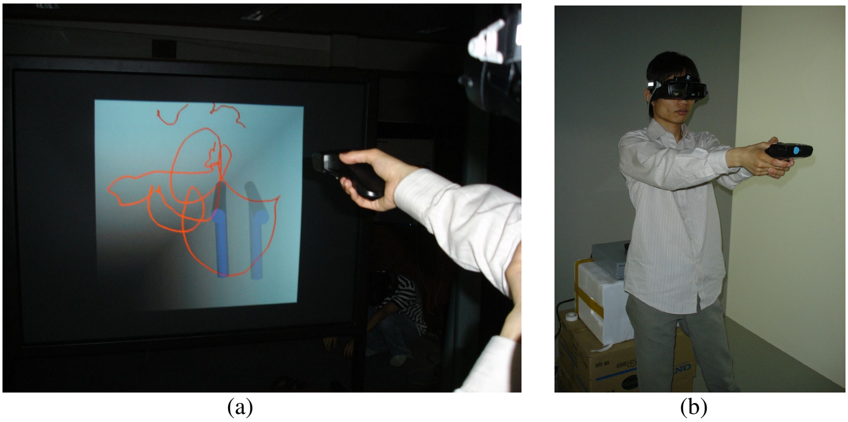


Fig. 2. Training Task 1: Free spray without the guide object. (a) A snapshot of a participant's carrying out the training task 1 with PROJECTOR. (b) A front view of him.

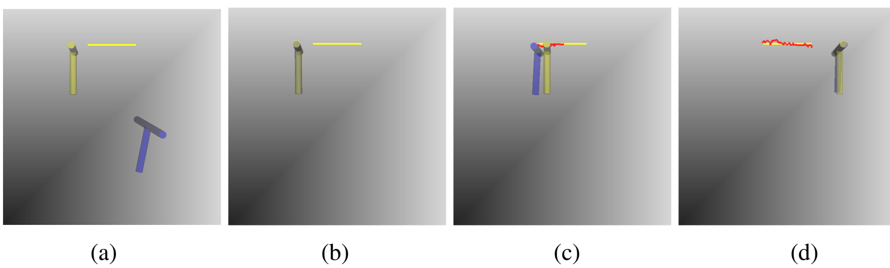


Fig. 3. Training Task 2: Spraying the paint in the given horizontal pattern while following the guide motion. (a) Initial state. (b) Matching the position and orientation of the painting gun with those of the guide painting gun. (c) Spraying the paint while following the guide motion. (d) Task completion.

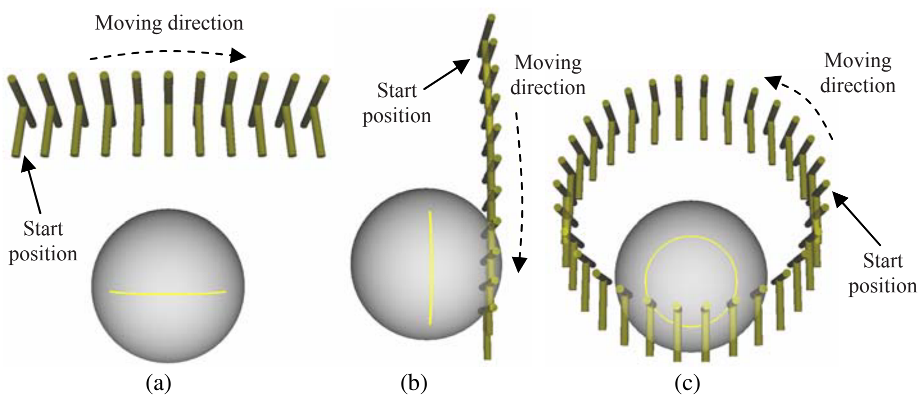


Fig. 4. The position and orientation of the guide painting gun profile at every second for each Actual Task. (a) For Actual Task 1: The total path length of the guide motion was about 35cm. (b) For Actual Task 2: The total path length of the guide motion was about 21cm. (c) For Actual Task 3: The total path length of the guide motion was about 63cm.

4.3 Procedure

Eighteen subjects participated in the experiment. Each participant visited our lab at an appointed time and performed 9 trials (1 trial for each task-display combination or 3 trials for each display system) in different orders. All of the sessions including preliminaries, calibration, training, task, as well as discussion time, lasted approximately one hour. The age of participants ranged between 19 and 35 (mean = 23.5 and standard deviation = 3.6), and among of them were 2 females.

Stage I: Preliminary Session. We introduced the experiment to the subject with the participant instruction which elaborated on the system and devices used in the experiment, as well as the task to be performed. After the introduction, the participant's vital personal information, such as gender and age, was collected.

Stage II: Calibration Session. First, the participant's inter-pupil distance (IPD) was measured with a pupilometer. And then, we performed the calibration procedure described in Section 3 in order to match the distance between the centers of two images for left and right eyes with her/his measured IPD. From this stage to the end of task trial session (Stage IV), the participant was required to always wear the see-through HMD although she/he performed trials with the large display only, since the adjusted viewport parameters might become unsuitable after the HMD was put off and worn again, the head tracking was always needed (note that the head tracker was attached to the HMD), and we wanted to eliminate the bias from having to wear the HMD itself.

Stage III: Training Session. To understand how to operate and carry out the required task, the participants were given a period of training prior to the actual task session. The training involved carrying out the three tasks designed for training (described in Section 4.2) with all of the three display systems.

Stage IV: Task Trial Session. Each participant performed the three actual tasks (described in Section 4.2) with all of the three display systems ($3 \times 3 = 9$ trials). In order to enhance the statistical reliability and avoid ordering effects, the orders of the nine trials were arranged according to the Digram-Balanced Latin Square design methodology [5].

Stage V: Debriefing Session. At the end of the experiment (after trying out all of the nine trials), the participants filled out the post-experiment questionnaire shown in Table 3.

Table 3. The comprehensive questionnaire.

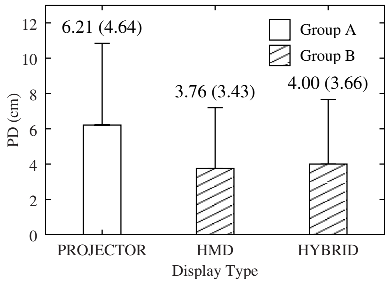
No.	Question
1	Was there any abnormal incidence while performing the given tasks?
2	During the task trials, what virtual objects did you mainly gaze on?
3	Did you experience any inconvenience in using the system? If you did, please describe.

5 Results

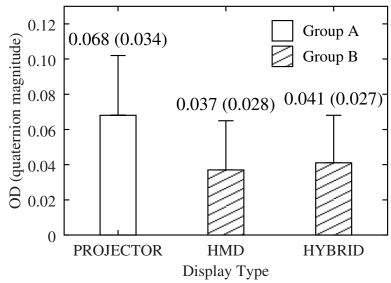
The means and the standard deviations of the dependent variables collected in the task trial session are summarized in Figures 5–6. A two-way within-subject ANOVA was applied on the dependent variables. The ANOVA results for the display type are also shown in Figures 5–6. According to the ANOVA, there were statistically significant differences among the display types for all of the dependent variables. However, the SNK (Student-Newman-Keuls) post hoc multiple comparison test revealed that only PROJECTOR was in a different group, that is, there was no significant difference between HMD and HYBRID. This means that HMD (the display type using HMD only) and HYBRID (the display type using both the large display and the HMD) exhibited higher task performance than PROJECTOR (the display type using the large display only). When PROJECTOR was used, the guide painting gun was often occluded by the wand or the participant's hands. However, when HMD and HYBRID were used, the painting gun was not occluded, since the LCD image of the HMD was always drawn on the real objects. In the debriefing session, seven participants reported this occlusion problem. We think that the occlusion problem of PROJECTOR had a negative effect on carrying out the given tasks.

On the other hand, as for the guide motion (or painting pattern) factor, the ANOVA revealed that there were significant differences for PD (position difference between the user and guide motions) and OD (orientation difference between the user and guide motions) but not for PPD (distance between the given painting pattern and the user painting result) (see Figure 6). However, there was no significant interaction between the display type and the guide motion type for all of the dependent variables (for PD, $F_{4,68} = 1.11$, $p = 0.36$, for OD, $F_{4,68} = 1.16$, $p = 0.34$, and for PPD, $F_{4,68} = 2.27$, $p = 0.07$). This means that the guide motion type alone had an effect on the task performance, but it did not have any mutual influence on the effects of the display type.

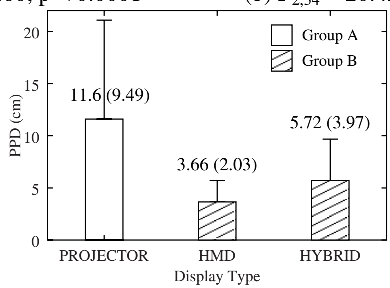
According to the replies to the questionnaire of the debriefing session, two participants reported that they had felt a little dizzy because the head belt of the HMD was too strongly tightened. Eleven participants replied to the second question that they had mainly gazed on the guide painting gun during the task trials, and the others replied that they had mainly gazed both on the target object and on the guide painting gun in an alternating fashion. As for the inconvenience in using the system, four participants pointed out the problem that the images projected on the large screen were dark. This problem was due to using the polarized light filters for stereoscopic imaging, and the brightness reduction caused by the half mirror installed in the HMD for providing the optical see-through function. We believe that the brightness reduction problem can be resolved simply by using brighter projectors. Two participants reported that the images displayed on the large projection screen and those on the LCD screen of the HMD were not fully registered, that is, the paint was sprayed on slightly different spots from the intended ones (at which they pointed the painting gun) for HYBRID. However, the experimental results show that the hybrid display system performed, despite the registration problem, up to par with the HMD.



(a) $F_{2,34} = 19.60$, $p < 0.0001$

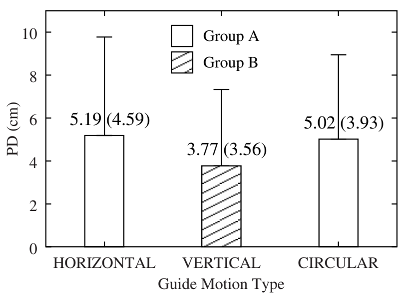


(b) $F_{2,34} = 20.42$, $p < 0.0001$

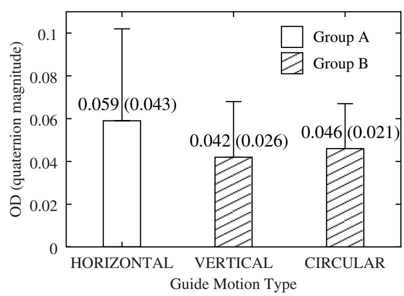


(c) $F_{2,34} = 27.52$, $p < 0.0001$

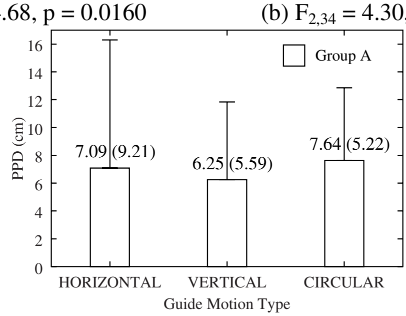
Fig. 5. Three task performance results for the display types: the means and (parenthesized) standard deviations, the ANOVA results, and the SNK-grouping results ($\alpha = 0.05$)



(a) $F_{2,34} = 4.68$, $p = 0.0160$



(b) $F_{2,34} = 4.30$, $p = 0.0217$



(c) $F_{2,34} = 0.81$, $p = 0.4537$

Fig. 6. Three task performance results for the guide motion types: the means and (parenthesized) standard deviations, the ANOVA results, and the SNK-grouping results ($\alpha = 0.05$)

6 Conclusions and Future Work

In this paper, we demonstrated that using a hybrid display that consisted of a large projection display and a see-through HMD was better for the guided-motion-following tasks than just using the large display only, thanks to the advantage of the HMD that eliminated occlusion of the guide motions. Although there was no significant difference between using the hybrid display and using the HMD only, we believe that using the hybrid display would have an advantage over the HMD only, because the hybrid display can provide much wider FOV (which was not a factor in the experiment in this work) than the HMD. Our future work is to experimentally validate this claim and to upgrade and deploy our system for a real industrial usage.

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