Using Mixed-Reality for Simulator Situation-Awareness

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ABSTRACT

It is neither practical nor feasible to deploy a conventional flight simulator with aviation units to maintain pilot proficiency. This is especially true for cockpits with side-by-side seating, for which the display system is inherently large. Operational Flight Trainers (OFTs) are the most practical way to keep proficient but are impractical when needed in tight spaces or with limited budgets.

This paper explores the use of a lightweight, stereoscopic Head-Mounted Projective Display (HMPD) with integrated retroreflective screen techniques and Mixed Reality (MR) technology as the display system for an inexpensive PC based simulator. It focuses on development of a low-cost, deployable full 360° field of view (FOV) display system, and provides technical background on retroreflective materials and HMPD lens design for this application.

An initial experiment design for a prototype cockpit simulator will be developed. The simulator is a proof of concept for a high fidelity flight simulator that is less expensive and more portable than those using conventional flight simulator techniques. This display system will provide an Augmented Reality (AR) low cost, deployable, full-FOV display system that can be applied to any human in the loop command and control (C2) system. For example, the same technology can be used for providing extraordinary Situation Awareness (SA) for operators in Air Traffic Control (ATC), Remotely Piloted Vehicle (RPV) and/or Unmanned Combat Air/Rotary Vehicles (UCA/RV) and Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems.

ABOUT THE AUTHORS

Javier (Jeff) Covelli is a Software / Systems Engineer for Northrop Grumman Information Technology (NGIT) and has been working in the Live, Virtual and Constructive military simulation and training field for over 20 years. While on active duty, he was a Navy S-3B Viking pilot and served as Training and Safety Officer for various squadrons and for the Flight Deck and Combat Information Center aboard the U.S.S. George Washington (CVN-73), where he earned Officer of the Deck (OOD) and Tactical Action Officer (TAO) qualifications. For the past four years he has worked on the Army sponsored Common Training Instrumentation Architecture (CTIA) program. He holds a B.S. Engineering Degree from the United States Naval Academy (USNA), an M.S.E.E. degree from the Naval Postgraduate School (NPS), an M.S.I.E. (Simulation and Training) from the University of Central Florida (UCF) and is currently finishing his Ph.D. degree in Modeling and Simulation at UCF.

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1.0 INTRODUCTION

Conventional flight simulators consist of an emulated cockpit, instruments, and controls with a virtual environment display ranging in sophistication (and price) from a simple flat PC monitor to wide field of view dome screens with bulky projectors and digital image blending techniques.

In an effort to cut costs, yet still improve pilot proficiency, the military has plans to decrease actual flight hours and increase flight training reliance on simulators. However, current military flight simulators are non-deployable. Taking a Navy carrier pilot as an example, the only method to conduct flight simulator training aboard an aircraft carrier, due to space limitations, is by using a desktop PC flight simulator. The limited FOV of a single monitor as a display for this type of flight simulation training is not as immersive as a wide FOV dome projection display on an expensive, yet non-deployable flight simulator. The desktop PC simulation approach is also impractical for providing realistic crew coordination training for aircrews.

An innovative new approach is to use Mixed Reality (MR), or more specifically Augmented Reality (AR) for a flight simulator display system that can be used in a small space with a low-cost, deployable simulator—or even with an embedded training system on the actual aircraft. Embedded training mode in modern fly-by-wire aircraft is possible if designed into the system, similar to the Army's Future Combat System (FCS) Embedded Combined Arms Team Training and Mission Rehearsal (ECATT-MR) concept [1]. Key to this concept is using a lightweight, stereoscopic Head-Mounted Projection Display (HMPD) projecting a computer-generated scene of the simulated environment onto a retroreflective screen fabric placed on the cockpit canopy [2]. The HMPD visualization system provides a realistic simulation experience. This approach is also applicable for cockpits with tandem or side-by-side seat configurations, and is an inexpensive alternative with several advantages that will be further described in detail.

1.1 TECHNICAL BACKGROUND

1.1.1 Mixed Reality Spectrum

Mixed Reality (MR) is a technique that merges real-world and virtual-world scenes to produce a new environment where physical and synthetic images merge both worlds in a single interactive environment. Paul Milgram defines a reality-virtuality continuum where MR displays are defined to include the real environment and the virtual environment with various categories in between [3]. Augmented Virtuality (AV) lies closer to the Virtual Reality (VR) end of the spectrum, where you inject a real image into a surrounding virtual environment. An example would be digital terrain texture mapping from aerial photography. AR lies on the opposite end of the spectrum, where one can superimpose virtual objects on a real environment. AR applications therefore are used in applications where a see-through environment is required to simulate the actual interior of the cockpit while augmenting the cockpit windows and walls with a simulated environment. This technique lends itself well to an actual live training exercise compared with other visualization techniques.

1.1.2 Mixed Reality Head Mounted Displays

Applications utilizing head-mounted displays (HMDs) for viewing merged virtual and real environments can be classified under two categories: video see-through or optical see-through. Video see-through displays use a head-mounted video camera (or set of cameras for stereoscopic vision) to merge the real environment image as normally seen by the eye with a computer generated virtual image [4]. Along with generating a virtual image based on head orientation, the image generator and rendering software must merge the real image from the video cameras at that same head orientation with the virtual image. This processing adds noticeable latency. Optical see-through displays eliminate the need for video cameras with the associated video rendering latency issue. For both video and optical see-through HMDs, users need a head-tracking device to synchronize the virtual and real objects, relative to the wearer's head orientation and position. When using chroma-keying techniques, head movements add additional latency by requiring generation of a new chroma mask to represent the Virtual Environment (VE) outside of the cockpit.

1.1.3 Microdisplay Technologies

Historically, the display of choice for simulations has been the CRT. Although low in cost, CRTs have inherent disadvantages with regard to weight, size (primarily in depth), heat generation, resolution, and power consumption [5]. Flat Panel Displays (FPDs), which are the display source for HMPDs, are based on a wide variety of technologies, each with distinct advantages and disadvantages as shown in Table 1.

Table 1: Comparison of Flat-Panel Technologies

FPD Technology	Advantages	Disadvantages
Active-matrix LCD	Full color; Superior image quality; Video speed	Limited viewing angle; Requires backlighting
Passive-matrix LCD	Low cost; Simple design	Reduced resolution; Slow response
Electro luminescent	Rugged; High resolution; Wide FOV; Long life	Full color questionable; Inefficient drive schemes
Plasma	Large size; High luminance	Affected by EM fields
Field emission	High luminance; High energy; Efficiency	Questionable reliability; Requires high voltage
Light Emitting Diode (LED)	Low cost	Lack of full color; High power requirement
Organic LED (OLED)	Low cost	Full color questionable; High power requirement
Vacuum fluorescent	High luminance; Wide FOV	Limited resolution
Electrochromic	High contrast	Problems with addressing techniques; Low pixel addressing speed

1.1.4 Head Tracking Devices

HMPDs require a head-tracking device to provide head pointing information to the image generator. Tracking devices have been discussed with different perspectives [6]. In summary, today, mechanical head trackers are not common due to the complexity of the physical mechanical linkage components. Magnetic head trackers are popular because of their small size and low cost. However, they are susceptible to distortion and noise by conducting metallic objects. On the other hand, optical head trackers can operate across a wide spectrum, making use of video cameras or infrared beams. These are becoming more popular because of their low latency, high accuracy and precision, and immunity to magnetic field distortion. They suffer however from occlusions. Acoustic head trackers normally operate in the radio frequency (RF) or ultrasonic spectrum. They are popular because of their overall relatively good performance and immunity to line-of-sight interference. While relatively rare, they may get some interferences however from other sounds. To minimize much of the limitations, head tracker devices have gone hybrid.

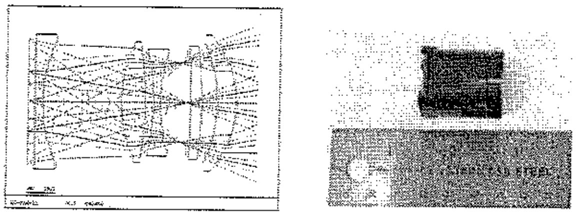
1.1.5 Head-Mounted Projection Displays

A HMPD is a type of optical see-through HMD. The internal components of the HMPD consist of a pair of projection lens, display source, beam splitter and an external retroreflective screen placed strategically in the environment. The concept of using an HMPD for a wide-FOV flight simulator was first introduced and patented in 1982 by James Harvey during U.S. Navy research to produce a pilot helmet mounted display with an eye-coupled area of interest [7]. The visualization system utilized a helmet-mounted opto-mechanical laser projector to produce a composite display of high- and low-resolution images. However, the focus of the research was to improve image generation efficiency, projected on a high-gain dome reflective screen, by diminishing resolution outside a head- and eye-tracked perimeter.

The HMPD, using a FPD display concept, was conceived in 1994 [8] by Fisher as a method of displaying binocular images observed by the user wearing the headset and then later patented [9]. Once the HMPD was introduced into the community, advancements in the HMPD technology were taken toward miniaturization of the projection optics module, the main contributor of weight. The miniaturization was developed by Rolland and her team and provided a robust, lightweight, and wide-FOV headset for augmented reality applications [10, 11]. The alternative to HMPDs with projection optics is an HMD that utilizes eyepiece design. The drawbacks limiting eyepiece design is that applications requiring large FOVs (i.e., > 20°) have extreme levels of image distortion (i.e., > 10%), correction of which increases the complexity, size, and weight of the optics. The solution to these major drawbacks is an HMPD that benefits by using projection optics with zero to negligible distortion (i.e., undetectable to the user's eye). In addition, an optical designer can scale the FOV of a projection system without increasing the system's complexity, image distortion, and optical weight.

1.1.6 HMPD Projection Optics Module

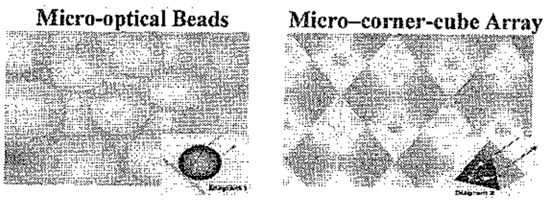
The original projection optics was based on an LCD microdisplay and a four-element lens [10], whereas the recent projection system using a small OLED microdisplay contains five elements shown in Figure 1 [13]. The optical elements comprise a combination of glass and plastic lenses with diffractive optical elements (DOE) and aspheric surfaces for lightweight and high visual acuity. In the design, both the aspheric and the DOE lenses are made of plastic to reduce the overall weight. With the development of the lightweight, custom-designed projection optics shown in Figure 1, a solution to significantly reducing the overall weight with a 42° FOV headset was achieved, resulting in an ultra-lightweight solution that can be comfortably worn on the head in prolonged usage.



(a) (b)

Figure 1: (a) Five-element projection optics. (b) The opto-mechanical packaging of the custom designed lightweight projection system

1.1.7 Retroreflective Materials



(a) (b)

Figure 2: Two types of retroreflective materials (a) microbeads; (b) microcorner cubes.

The HMPD system uses a retroreflective material as an optical component with high gain efficiency to compensate for the limited amount of illumination provided by the miniature display. Currently, two types of COTS retroreflective material are commercially available, both shown in Figure 2: micro-optical beads and micro-corner-cube arrays. Although these retroreflective screens provide high gain efficiency, their intended purpose is conspicuity, such as traffic safety applications. The micro-optical bead material was fabricated with randomly spaced and curved bead microstructures that have a lower efficiency retroreflection compared with the micro-corner-cube array, which uses tiled pyramidal microstructures with planar surfaces.

1.1.8 Current HMPD Prototype

Prototype headsets with custom designed projection optics, COTS miniature display, and beam splitter were assembled [14]. Although the latest HMPD technology has decreased the overall weight of the headset, as well as the distortion, while still providing a high resolution image (i.e. maximum of 2 arc-min of angular blur given ideal retroreflection) with a large FOV, the use of an external retroreflective screen mounted in the environment may sometimes constitute a hindrance, and surely does not allow for full mobility in a natural environment. Additional research was performed toward removing the retroreflective material from the environment and integrating it within the headset, and will be further discussed in the paper.

1.1.9 The Concept of the Fabric-Integrated HMPD

By integrating the retroreflective material within the headset we can capitalize on all of the benefits of the projection based HMDs. The conceived HMPD now has mobility as a key feature to the next generation HMPD technology [13].

The concept of the environment fabric-free HMPD integrates the retroreflective material along an alternate path given by the 50/50 beam splitter (i.e. "Path 2") as shown in Figure 3. With the integrated retroreflective material along Path 2, we image the retroreflective material virtually in the environment by placing a lens (L_1) between the projection optics and the retroreflective material. Furthermore, the light emitted by the miniature display entering L_1 also exits at the same location after being retroreflected by the material, producing no additional aberrations in our rendered image. This development has increased the capability of the HMPD technology from indoor use to outdoor use, as well as applications where retroreflective material placed in the environment is not practical. Interestingly, the new construct can also be used with additional retroreflective material in the environment if desirable, but the key working principle of this wearable outdoor display is that having also retroreflective material along Path 1, as previously suggested, is not a necessity. And for outdoor wear, no Path 1 material will be used indeed, only Path 2, which makes for the novelty of the approach.

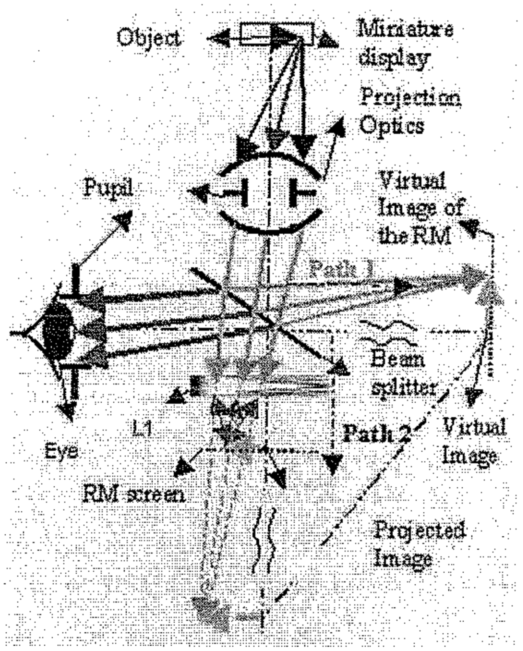


Figure 3: First order layout of the wearable HMPD with integrated retroreflective material along Path 2

2.0 SIMULATOR CONCEPT

A proof of concept flight simulator is needed to conduct initial usability testing. A conceptual low cost PC based flight simulator prototype system would consist of the following main systems and subsystems:

- Instructor Operating Station (IOS)
  - Scenario generation
  - Simulation control
  - Data collection and replay
- Flight Simulator (MS Flight Sim)
  - Flight model
  - Sound definitions
  - Panel definitions
- Interface Device
- Display system
  - CRTs and
  - HMPD (or HMD)
- Cockpit
  - Cockpit shell
  - Cockpit panels, instruments & displays
    - Glass cockpit (all digital) or
    - Replicated panels (analog & digital or Photo)
  - Flight controls (COTS)
  - Sound system

2.1 Display System

The conceptual display system consists of two interchangeable systems as shown in Figure 4: a conventional CRT display monitor or the HMPD described in section 1.1.9. The reason for having two options for a display system is to test user reaction with the new HMPD as compared with a conventional CRT display system.

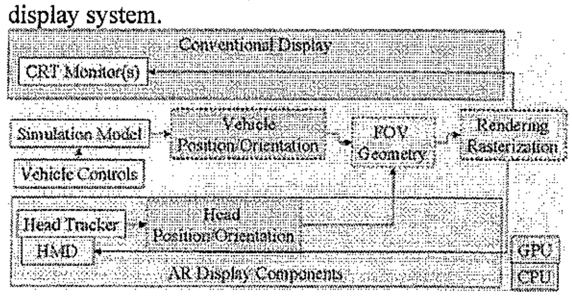


Figure 4: Conceptual simulator architecture with interchangeable CRT and HMPD systems

Using a HMD adds additional latency, as described in 1.1.2 and depicted in Figure 5. Note that the additional steps of generating a chroma mask and merging the virtual and real images by the CPU adds latency. However, HMDs should still be considered as a comparison for usability testing as described in section 3.1.

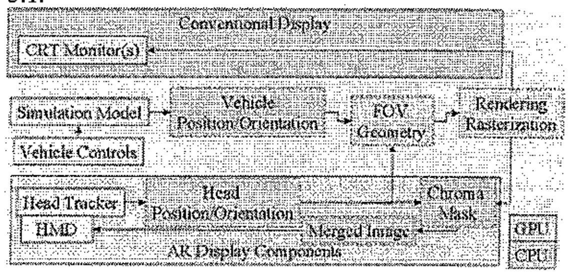


Figure 5: Alternative simulator architecture with interchangeable CRT and HMD systems

2.2 Cockpit

The conceptual cockpit consists of a simulator shell, which can be a lightweight fiberglass (or cardboard) replica of the aircraft being modeled. Cockpit windows will consist of one or more CRT monitors for the conventional configuration. The AR display configuration will replace the CRTs with the retroreflective fabric if using a HMPD or a blue screen if using a HMD. Cockpit panels will ideally be of a glass cockpit design, making optimum use of flat panel displays with digital panel representation. Where glass cockpit panels are not practical, panels will consist of low to medium resolution panel replicas with a USB interface or they can even be a lower cost photograph image.

3.0 USABILITY TESTING

3.1 Augmented Reality Experiment Design

The goals for usability testing are to measure and compare user interactions with a conventional CRT display and AR display flight simulator. Primary analysis will involve ease of use (e.g. task times, user errors and recovery from errors) and user satisfaction. Task design involves safe control of vehicle and navigation, including take-off and landing, from point A to point B. Participants will be recruited from the university and surrounding simulation industry.

3.1.1 Within Group Design

Since the volunteer participant levels of proficiency with simulation are expected to vary, a quasi-experimental design using questionnaires and spatial ability tests will aid in participant group matched random assignment [18]. All group blocks will be briefed on the conventional and AR simulator control procedures and will perform the same tasks ranging from easy to difficult. Post-flight debriefs will provide user feedback regarding satisfaction in each simulator configuration.

3.1.2 Variability

By dividing the participants into group blocks representing a certain level of proficiency, within group variability can be controlled for the experiment error variance will be minimized [19].

3.2 Specific Application Testing

Characteristics of AR, favorable or not, will be tested in this flight simulation application.

3.2.1 Registration errors

For AR systems, registration and sensing errors are two of the biggest hurdles to overcome [16]. Registration is properly aligning virtual objects with the real world. Registration error sources include optical distortion, tracking system errors, mechanical misalignments, and dynamic errors involving system end-to-end delays. Sensing errors involve head tracking system and real object recognition errors and contribute to registration errors. Since the HMPD maximum angular blur is roughly the same as the human eye visual acuity [17], a properly registered HMPD AR simulator image shouldn't provide visual conflicts to the user.

3.2.2 Optical vs. Video see-through

As mentioned earlier, the HMPD is an optical see-through AR device. Video see-through HMDs that provide a combined real world video with VE images are becoming more common [3, 6, 14, 16]. There are advantages and disadvantages with these approaches that are worth investigating further in a flight simulator or other virtual simulation application.

3.2.3 Data collection

Simulator tasks will be designed to test basic tasks that can be influenced by registration errors. Post-flight debrief questionnaires will be designed to gather task feedback from the user, comparing the conventional and AR simulators. Obvious areas of interest are issues with motion sickness, noticeable image resolution differences, apparent image distortion, and overall comfort with the simulation device.

4.0 CONCLUSION

The driving force behind the research for this AR application is validating the concept of embedded training with an HMPD-based simulator; using actual operational vehicles and their subsystems in training mode to conduct deployable embedded training. The example of a Navy aircraft carrier aircrew simulator emphasizes the need of having an inexpensive deployable simulation system that allows the warfighter to train in their weapon platform or an inexpensive emulation. The ultimate vision is using one common, deployable training solution; an HMPD-based simulation system for all type of virtual simulations to conduct individual procedure training or coordinated interactive mission rehearsal. An environment fabric-free HMPD also makes embedded AR training possible when dismounting a vehicle.

The next step towards this vision is to design an AR usability experiment, along with development of the described prototype HMPD-based simulator. The usability testing involves Human Factors research and experiments with AR, using existing HMDs and the latest ultra-lightweight HMPD technology. The research will provide pros and cons of using AR displays compared to conventional displays for this specific simulator application and will provide insight for other type of embedded virtual simulators that keep the "reality" in the simulation.

ACKNOWLEGEMENTS

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Acronyms

AR	Augmented Reality
ATC	Air Traffic Control
AV	Augmented Virtuality
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
COTS	Commercial Off The Shelf
CRT	Cathode Ray Tube
FCS	Future Combat System
FOV	Field of View
FPD	Flat Panel Display
GOTS	Government Off The Shelf
HMD	Head Mounted Display
HMPD	Head Mounted Projection Device
IOS	Instructor Operating System
LOS	Line of Sight
MR	Mixed Reality
OFT	Operational Flight Trainer
RF	Radio Frequency
RPV	Remotely Piloted Vehicle
SA	Situation Awareness
UCA/RV	Unmanned Combat Air/Rotary Vehicle
VE	Virtual Environment
VR	Virtual Reality