See Through HMDs—New Technology to Support Live Training Applications

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ABSTRACT

The U.S. Army envisions a fully developed Augmented Reality (AR) system to provide the Warfighter with an exceptionally realistic training experience. The real time blending of virtual objects into the live training environment would permit the Warfighter to train with and against virtual 3D objects, displaying realistic behavior. The key interface into a live AR environment is the Head Mounted Display (HMD). Currently most off-the-shelf HMDs are either the "fully occluded" type (used for virtual reality applications) or the "video see through" type (used for mixed reality applications). While widely available from industry at reasonable costs, these types of HMDs are limited by restricted fields-of-view and have significant video latency, both are major hindrances. Neither is suited for the live training environment. On the other hand, an "Optical See-Through-" type of HMD (OST-HMD) would permit one to directly view the live environment through a transparent lens—using natural vision and a normal field-of-view—as opposed to viewing occluded video playback directly from HMD mounted cameras. Therefore, OST-HMDs should be much better suited to support unrestricted movement throughout a live physical training environment. Currently, when OST-HMDs are used in the live environment, the virtual images produced are see-through and "ghostly", thus their appearance is unrealistic. There is a need to increase the capability of OST-HMDs in order to produce 3D virtual imagery of sufficient opaqueness and contrast resolution where viewers believe the virtual objects are a natural part of the live environment. In order to address this technology gap, the U.S. Army Research Laboratory, Human Research and Engineering Directorate, Simulation and Training Technology Center (ARL-HRED-STTC) and Trex Enterprises Corporation are conducting research into improving the quality of OST-HMDs for live training applications. This paper will review requirements as well as the most recent results of ongoing research in this technology area.

ABOUT THE AUTHORS

Frank S. Dean, Jr. is an engineer and Science & Technology (S&T) manager at the U.S. Army Research Laboratory, Simulation and Training Technology Center (ARL-HRED-STTC), Orlando, FL. He currently works in the Ground Simulation Environments Division conducting research and development in the area of dismounted Soldier training and simulation. As an S&T Manager, Mr. Dean's current interests revolve around researching Augmented Reality (AR) technologies/techniques and their potential application in the live training environment. He has developed long-range plans, including identifying critical core research areas that require concentrated effort for the eventual development and transition of these cutting edge technologies to the Warfighter. He has also authored, co-authored and presented a number of papers and articles on various aspects of augmented and mixed reality. Mr. Dean has over 30 years of military and government civilian service. Mr. Dean earned a Bachelors of Science in Electrical Engineering from the University of Miami and his Masters of Engineering Management from George Washington University. He is also Level III certified in Science & Technology Management and Project Management.

Dr. Mikhail Belen'kii serves as Director of Trex Enterprises' Remote Sensing and Navigation Business Unit, a multi-million dollar per year business area. Over the last ten years, Dr. Belen'kii grew this new business area from multiple Phase I and II SBIRs, including the development of novel star tracker technologies for forward observers, Celestial Navigation technology for GPS denied environment, and development of advanced Head Mounted Displays for commercial and military applications. Dr. Belen'kii is a nationally recognized expert in the area of atmospheric optics, laser beam propagation, novel laser-based remote sensing system development and imaging through atmospheric turbulence. Dr. Belen'kii is a member of SPIE and a Fellow of the Optical Society of America. Dr. Belen'kii has authored and co-authored three books and more than 210 technical papers. He holds 8 U.S. Patents. Dr. Belen'kii received a B.S. and a Ph.D. in Physics from the Tomsk State University in U.S.S.R.

Dr. Larry Sverdrup is currently a Senior Scientist at Trex Enterprises. Previously, he has worked for Ophthonix, Inc., as a Scientist (2004-2009) and Western Research (1987-2004). He has over 20 years of experience working in imaging and vision based research. His primary role at Ophthonix was developing high-order correction systems for spectacles, providing Lasik levels of foveal correction but in an off-eye application. Dr. Sverdrup currently holds 8 patents, more than 8 publications, and is actively involved in AAAS, SPIE, and OSA. Dr. Sverdrup has a PhD in applied physics from Caltech, and a BA in physics from Reed College.

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THE PROBLEM

The "Optical See-Through" Head Mounted Display (OST-HMD) is a part of a fully developed Augmented Reality (AR) system and the key interface into a live augmented reality environment. This display will provide the Warfighter with a realistic training experience by blending the virtual objects into the live training environment. Applications of such a display are diverse and include military training, assisted surgery, video games, and everyday life. Several examples of applications of OST-HMD are shown on Figure 1.

Figure 1: *Examples of applications of OST-HMD (MicroVision, 2012; How Stuff Works, 2001).*

Most commercially available HMDs have several limitations. In particular, these displays typically have a limited display field-of-view and at least partially block the see-through field-of-view. As such they do not support unrestricted movement through a live training environment and virtual objects are not visible outside of the display field-of-view. In some models, video latency parameters are objectionably slow. Finally, in "optical see-through," or mixed reality displays, where virtual images are simply superposed on top of the background scene, the virtual objects often appear ghostly and unrealistic. Because the human brain utilizes occlusion (among many other clues) to determine range, it is sometimes difficult to determine the distance between the Warfighter and the virtual object. The problem is lack of occlusion, or blocking, of the background scene by virtual objects. Two examples of augmented reality objects illustrating the lack of occlusion are shown in Figure 2.

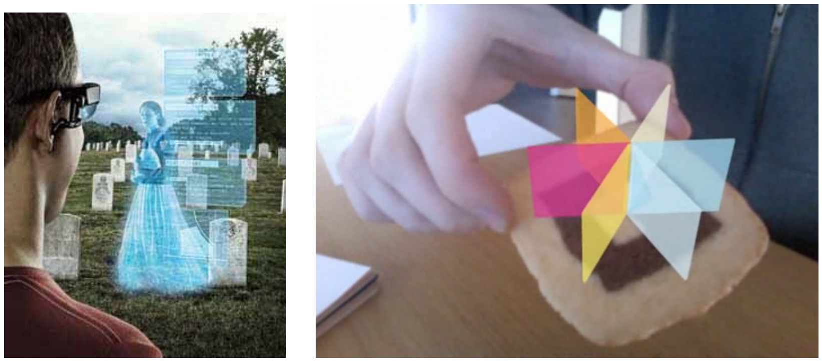


Figure 2: *Examples of augmented reality objects illustrating the lack of occlusion (Google Images, 2013).*

One general approach for this problem is simply to darken the entire see-through image, at least in conditions of bright sunlight. Potentially, one can incorporate sunglasses, or photochromic glasses, in the HMD. However, permanent sunglasses are not useable in lower light conditions, and conventional photochromic sunglasses operate too slowly. They will impair situational awareness for the several minutes required for sunglasses to alter their transmission. Furthermore, these solutions simply suppress the background light to make virtual objects more visible, rather than providing a method to make virtual objects appear more solid and blend, in a realistic manner, with the background scene. Darkening the entire lens in bright conditions is useful for providing a comfortable display and optimizing see-through vision. It also makes it easier for the display to compete with background light. However, ideally the darkening and clearing would be programmable with negligible transition duration. It should be possible to quickly turn off the darkening when walking into a dimly lit building from bright sunlit conditions.

Presentation of spatially isolated data such as text or symbology can be washed out in the presence of a sufficiently bright background. To ensure instant readability, the data could be presented over an opaque box of appropriate size, which temporarily blocks, or reduces see-through transmission, in a restricted area. In this mode, the opaqueness must have some limited spatial resolution, which need not be high and once again, high switching speed.

Finally, in currently available OST-HMD solutions, virtual objects such as enemy combatants will look ghostly against most natural backgrounds. Because occlusion is utilized by the brain as a cue to depth, depth perception of AR objects will be adversely affected. To provide a realistic appearance for the virtual objects, a programmable technology is needed, which provides opaqueness on demand at video rate with the required spatial resolution.

CURRENT OFF-THE-SHELF SOLUTIONS

There are two known methods for obtaining programmable occlusion to generate virtual objects with a solid appearance: (1) Full occlusion with a video relay (Haller, Billinghurst, Thomas, 2006) and (2) See-through optical relay with programmable LCD blocker (Mulder, 2006). Each method has its advantages and disadvantages as described below.

Full Occlusion with Video Relay

With full occlusion and a video relay, all of the occlusive depth cues are provided in software. There is no longer a difference between virtual objects and real objects in the sense that they are both presented by the display. This type of display is currently available, and affordable. See Figure 3a. The drawbacks of this display include the following:

i) Situational awareness is compromised due to limited camera and display resolution and field-of-view.

ii) There is a small perspective error in that the entrance pupil of the camera replaces the entrance pupil of the eye. The eyes will see what the cameras will see, but the cameras cannot be where the eyes are located. The wearer will have to adapt to a situation in which his eyes have been apparently moved forward approximately one inch.

iii) Latency can become an issue when large amounts of data have to be relayed from the cameras to the displays.

Fundamentally, the problem is that the full occlusion with video relay cannot reproduce unimpeded see-through vision of the live training environment and cannot support unrestricted movement throughout a live physical training environment.

a) *b)*

Figure 3: *The Vuzix Wrap 1200AR HMD (Vuzix, 2013) (a); The ELMO-4 see-through HMD with occlusion circa 2003 (Kiyokawa, Billinghurst, Campbell, Woods, 2003) (b).*

See-Through Optical Relay

It is often assumed that this method is the only alternative to full occlusion with a video relay. The purpose of the optical relay is to place a programmable light-blocking device such as an LCD in focus with the scene so that light behind virtual objects can be blocked with a high degree of resolution. However, this concept has its own drawbacks:

i) Situational awareness is compromised in most optical relay schemes, which typically restrict the see-through field of view;

ii) Active matrix LCDs can provide a fast response, but some have limited optical density for the full color gamut, and limited pixel count is an issue;

iii) LCDs require the use of a polarizing filter and consequently always block 50% of the light. The large number of optical components results in very low see-through transmission. This means that the scheme is not useable at night;

iv) Optical relay schemes typically result in bulkier and heavier devices (see Figure 3b). Sony has suggested that in order to wear a see-through display comfortably for 2 hours, it must weight no more than 80gms (Tanaka 2008); and

v) The optical relay causes a perspective error similar to the video relay concept, although ELMO-4 cleverly reduced this to the thickness of one mirror.

In summary, current off-the-shelf methods of providing opaqueness for AR application entail substantial limitations. The goal of this research conducted by the U.S. Army Research Laboratory, Human Research and Engineering Directorate, Simulation and Training Technology Center (ARL-HRED-STTC) and Trex Enterprises Corporation is to develop a novel OST-HMD with opaqueness for live training applications, which will overcome the above limitations.

NOVEL CONCEPT OF OPAQUENESS-IN-THE-LENS

Trex is developing a new type of OST-HMD with the format of wrap-around safety goggles, which provides essentially unimpeded natural see-through vision to maximize local situational awareness, and a large display Field-Of-View (FOV) to immerse the Warfighter in the live training environment. In the proposed device, a curved primary mirror in front of each eye allows for the wrap around safety goggle format, providing unimpeded see-through FOV, and also the possibility of a large display FOV. A novel method of eye-tracking and for generation of the eye-box is included in the design. The architecture of the new display provides a natural method for implementing the proposed new technique for generating opaqueness behind virtual objects. The aim of this paper is to describe the novel opaqueness concept. Details regarding the new OST-HMD and method of implementation of the new opaqueness technique will be described in future publications.

To solve the problem of opaqueness generation for augmented reality in OST-HMDs, a new approach denoted "opaqueness in-the-lens" is proposed. That is, opaqueness is generated at video rates directly in the lens of the HMD. The opaqueness is locally programmable so that the transmission of lens in selected regions where virtual objects appear can be varied quickly, and washout due to a bright background is avoided.

The proposed method of occluding background scenery in the lens of an OST-HMD has none of the disadvantages listed in the previous section, but has limited opaqueness resolution because opaqueness generated in the lens is not in focus with the displayed virtual objects. In the next section, the requirements for opaqueness resolution will be examined quantitatively.

MODEL FOR OPAQUENESS RESOLUTION

The opaqueness resolution depends upon several variables including the diameter of the entrance pupil of the eye D_P, the diameter at the lens of light from a distant point source which contributes to the image in the eye D_L, the eye relief ER, and the range to the point source in the image R. A model of this is shown in Figure 4. The diameter of the darkened spot on the display lens is D_D.

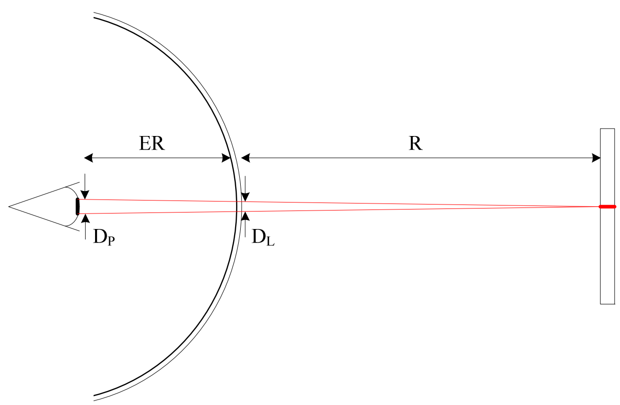


Figure 4: *Parameters relevant to the resolution of opaqueness.*

D_L is related to the other parameters by the relation:

$$D_L = \frac{R}{ER + R} D_P \tag{1}$$

In general, objects viewed are at a distance R that is large compared to the eye relief of the display. Hence a good approximation is that R >> ER. This in turn implies that:

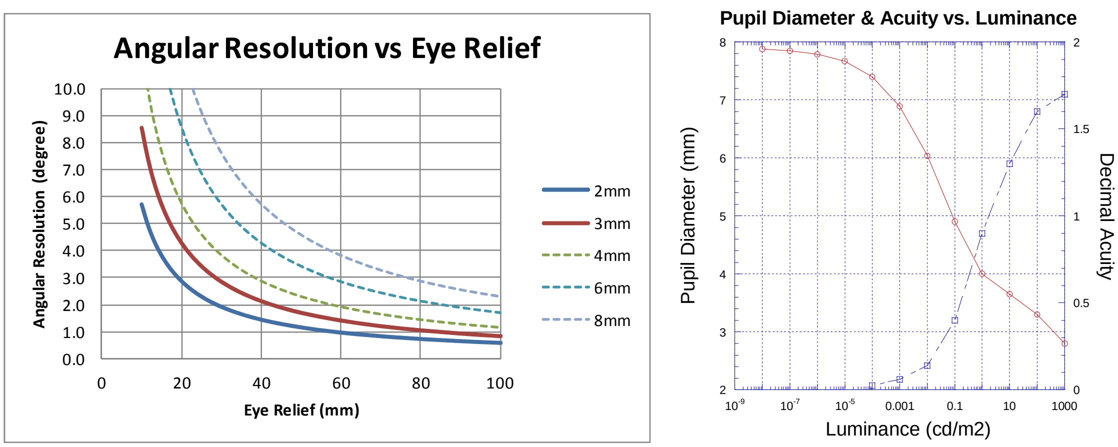
$$D_L \cong D_P \quad (R >> ER) \tag{2}$$

If the point being viewed in Figure 1 is to be replaced with a virtual image point, one option is to darken the lens over a diameter $D_D = D_L \approx D_P$. This would block all of the light from the background scenery coincident with the virtual image point. If $D_D < D_L$ then the opaqueness resolution is increased, but the degree of opaqueness is decreased. Thus it is possible to trade degree of opaqueness for resolution of opaqueness.

The dark spot on the display lens subtends an angle at the eye of approximately:

$$\theta \approx \frac{D_D}{ER} \tag{3}$$

This is the nominal resolution of the opaqueness. In Figure 5a, angular resolution is plotted versus the eye relief for various pupil diameters. Larger eye relief and smaller pupils are associated with higher resolution. In bright sunlight, the pupil of the eye reduces to its minimum value, which is approximately 2mm. In factory or office conditions, the diameter of the pupil is approximately 3mm in diameter, which typically provides optimum acuity. The pupil does not expand to larger values unless the lighting is poor. In that case, visual acuity is dramatically reduced. See Figure 5b. When acuity is very poor, it is less pertinent that the opaqueness resolution is reduced. Also, in darker conditions the background is generally dark, and opaqueness is less of a requirement. Therefore the most important cases are for pupil diameters of 2-3mm. In this case, for an eye relief of 60mm the angular resolution is of the order of 1°.



a) *b)*

Figure 5: *Nominal opaqueness angular resolution versus eye relief and pupil diameter (a); Pupil diameter and decimal acuity versus luminance (Atchison, Smith, 2002); the brightness of a typical computer monitor is 100cd/m^2 (Arecchi, Messadi, Koshel, 2007); decimal acuity of 1.0 corresponds to 20/20 (b).*

In the military training application, a typical virtual object might include an enemy combatant. The angular size of a nominal adult versus distance is shown in Figure 6. For purposes of estimation, the height is taken as 6-foot and the width is taken as 1.5 foot. It is apparent that the long dimension (height) of a human always exceeds the opaqueness resolution, even at 100 foot distance. At a 100 foot distance, the width of a typical adult approaches the resolution of opaqueness.

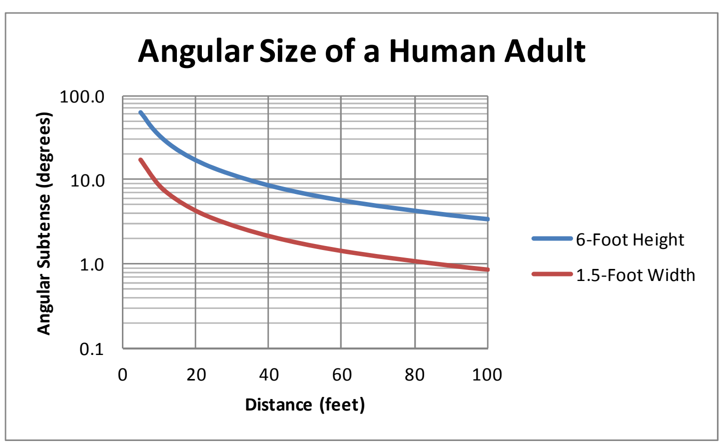
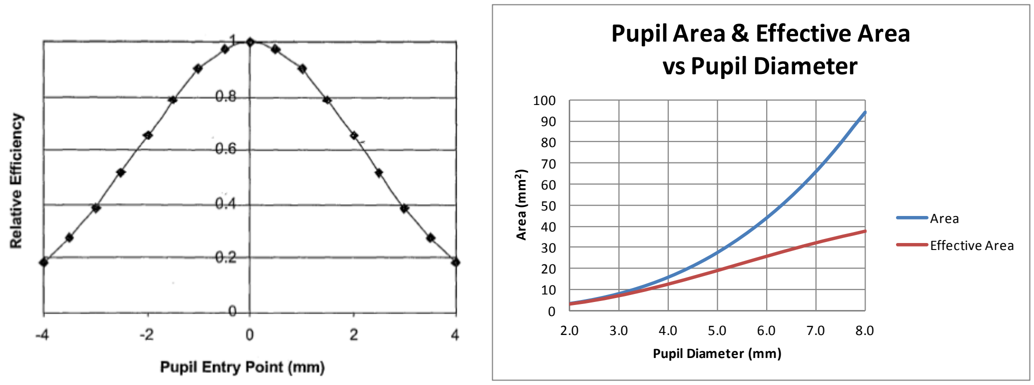


Figure 6: *Angular size of a nominal adult versus range*

Large Pupils

The penalty when $D_D < D_P$ is not as severe as it might seem. The Stiles-Crawford effect causes light entering the pupil of the eye to have varying visual efficacy depending upon where in the pupil the light enters. Light entering the edge of the pupil has greatly reduced visibility compared to light entering the center of the pupil. See Figure 7a. The Stiles-Crawford effect only pertains to foveal vision because the effect is caused by the waveguide nature of the cone sensors located in the fovea.



a) *b)*

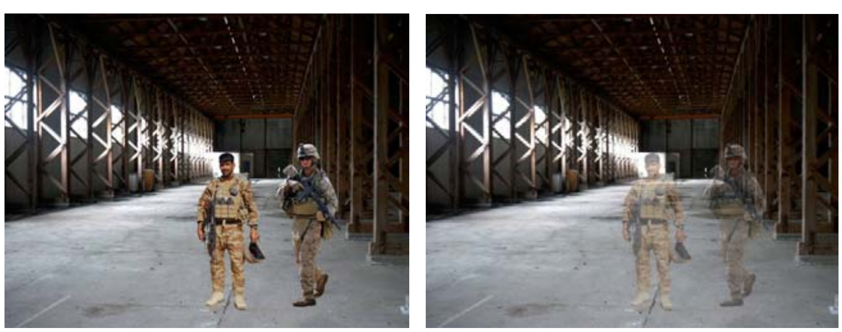
Figure 7: *The Stiles-Crawford effect – relative visibility of light versus pupil entry point (Schwiegerling, 2004) (a); Cumulative area and effective area (after inclusion of Stiles-Crawford apodization) versus pupil diameter (b).*

The entrance pupil diameter of the human eye ranges from approximately 2mm in bright sunlight to 8mm in the dark. Figure 7b presents the results of a calculation of the cumulative and effective areas (after inclusion of the Stiles Crawford effect) versus pupil diameter. Whereas pupil area increases with a quadratic dependence versus pupil diameter, after inclusion of the Stiles-Crawford effect, the visually effective increase in light collection is more linear with pupil diameter.

For foveal vision the effective amount of light from a point source increases in approximately a linear rather than quadratic fashion versus pupil diameter. The good news is that failure to mask light from the outer edge of the pupil does not result in a large increase in background light as the pupil area calculation would suggest. Instead there is only an incremental linear increase. What this also implies, is that degree-of-opaqueness can be traded linearly for resolution-of-opaqueness. If, instead of 100% opaqueness, one were to accept 50% opaqueness, the resolution could be doubled. These are decisions involving the software associated with operation of the display

EDGE EFFECTS

The proposed concept provides a method to make the interior of virtual objects fully opaque. However, due to the limited opaqueness resolution, the optimum approach for creating opaqueness at the edges of virtual objects remains to be determined. Two options include (1) creating full opaqueness even at the edges, but causing depression of background light just outside of virtual objects (dark halo) or (2) keeping full opaqueness away from the edges, which allows for some washout at the edges. In order to obtain a preliminary answer, these effects were simulated in the software. Figure 8 shows a pristine image of two Soldiers (a), virtual Soldiers without occlusion (b), virtual Soldiers with internal occlusion and edge transparency (c) and virtual Soldiers with no transparency but suppressed background light near edges (d). One immediate conclusion is that either of (c) or (d) is far superior to the case of no occlusion (b).



a) *b)*

c) d)

Figure 8: *(a) pristine image; (b) virtual Soldiers with no occlusion; (c) virtual soldiers with internal occlusion and edge transparency, a post is visible through the helmet; (d) virtual soldiers with no transparency but suppressed background light near edges.*

An informal poll of observers overwhelmingly suggests that under-filling a virtual object with opaqueness is visually preferred to overfilling the virtual object. Hence it is preferred that virtual objects have some transparency at the edges, rather than carry "halos" of opaqueness. 100% opaqueness is always available in the interior of a virtual object, a resolution distance or more from the edge of the object. Near the edge of a virtual object, a reduced degree-of-opaqueness could be offered in order to improve opaqueness resolution in the edge region. However, this is a tradeoff that can be resolved by studying variations in the software, once the hardware has been fully developed.

HARDWARE BASED DEMONSTRATION

The proposed concept for solving the problem of opaqueness has none of the limitations inherent in the conventional off-the-shelf approaches. The wrap-around safety goggle format of the proposed display is ergonomic, compact, and lightweight and has excellent see-through transmission and field-of-view. The challenge with the opaqueness-in-the-lens concept is reduced spatial resolution. However, it has been shown that if the opaqueness is confined to the interior of the virtual objects, the transparency near the edges is not readily noticeable. A hardware-based demonstration of the proposed opaqueness-in-the-lens concept is shown in Figure 9. Virtual objects appear solid, and the resolution at the edges is dominated by the displayed virtual object rather than the opaqueness (see Figure 9c).

a) b) c)

Figure 9: *Hardware demonstration of Opaqueness-in-the-Lens Technology: Background scene (a); Background scene with an overlaid AR green disc with "ghostly" appearance (b) and opaqueness-in-the-lens is activated providing occlusion (c).*

SUMMARY & CONCLUSIONS

Conventional methods for generating opaqueness and occlusion for augmented reality consist of "optical relay" and "video relay", both of which entail serious limitations. The opaqueness-in-the-lens concept avoids all of the limitations associated with optical relay and video relay approaches, but offers limited spatial resolution.

It has been shown that for reasonable HMD parameters, opaqueness-in-the-lens can provide a resolution of the order of one degree. This is sufficient to make the interior of a virtual enemy combatant opaque without the creation of an external “opaqueness halo” at ranges up to 100 feet. Degree-of-opaqueness can be traded roughly linearly with opaqueness resolution. An informal poll of observers viewing simulated images indicates that most people prefer interior opaqueness without an external opaqueness halo. In this situation, the resolution of the edge of the virtual objects is defined by the display resolution, which is much higher than the opaqueness resolution. Edge transparency is less noticeable than interior transparency. Interior opacity removes the ghostly appearance of virtual objects.

When sunlight causes pupils to contract below 3mm in diameter, acuity becomes limited by diffraction and can actually be reduced (Bennett, Rabbets, 2007). A fringe benefit of addressable, video-rate opaqueness-in-the-lens includes a fast sunglass mode, in which the lenses can be made to darken in bright sunlight for both comfort and to optimize vision. Due to the video rate operation, the sunglass mode can be cleared instantly as the wearer moves from bright sunlight into a darkened building, optimizing situational awareness. With clear lenses, the HMD is useable also at night. Another fringe benefit is that when augmented reality data is displayed, it can be presented against a temporary opaque box of appropriate dimensions to prevent washout in the presence of a bright background. The switchable opaqueness can even be used to electronically convert the HMD to a virtual reality mode, in which all see-through is blocked. For instance, upon laser attack, the lenses of a platoon could be made to go dark, while the display switches to helmet mounted cameras.

The proposed mechanism for implementation of video-rate opaqueness-in-the-lens has been demonstrated in a laboratory setting. Future research is required to ascertain the attainable optical density versus wavelength across the visible spectrum. Preservation of the limited opaqueness resolution in an HMD required development of a novel eye-box technology. These and other details will be presented in future publications.

Applications of an OST-HMD with opaqueness are diverse and include military training, military combat, assisted surgery, video games, and everyday life. Those who can best interact with computers will have the greatest advantage.

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