DISPLAYING THE BATTLESPACE ENVIRONMENT: EVOLUTION OF A HEAD-MOUNTED DISPLAY

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ABSTRACT

In today's increasingly sophisticated simulation world, a realistic, high intensity, task-loaded display of the battlespace environment has become the expectation of the military user community. To effectively train aviation aircrews, the visual system must support realistic collective/combined arms training with the required fidelity to fly nap-of-the-earth (NOE) or conduct multi-ship operations. Meeting this high level of expectations requires that the visual system be capable of performing all necessary collective tasks and supporting individual tasks with no negative training transfer or physical impacts on crewmembers. An evolving technology that can meet these needs is the Head-Mounted Display (HMD). This paper will address the use of HMDs in aviation simulators and will follow the evolution of the SIM EYE XL 100A from its early Wide Eye™ stage, to its current use in the Army's Aviation Combined Arms Tactical Trainer – Aviation (AVCATT-A) Reconfigurable Manned Simulator program. Finally, it will address possible future improvements that can be incorporated into the HMD to further satisfy Army aviation users.

BIOGRAPHIES

Jim Melzer is a Product Manager for Head-Mounted and Miniature Displays at Kaiser Electro-Optics, in Carlsbad, California. He has been designing and building HMDs for over 17 years for a variety of applications including medical, professional, training and simulation, fixed-wing and rotary-wing, and dismounted infantry. He holds four patents in HMD design and has authored over 25 technical papers including a co-edited book on the subject - *Head-Mounted Displays: Designing for the User*, published by McGraw-Hill.

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INTRODUCTION

In the increasingly sophisticated world of simulation, the military user community has come to expect a realistic, high intensity, task-loaded display of the battlespace environment. To effectively train aviation aircrews, the visual system must support realistic collective/combined arms training with the required fidelity to fly nap-of-the-earth (NOE) or conduct multi-ship operations. The visual display system must meet these requirements and must be low cost, deployable, provide a full-color, wide instantaneous field-of-view (FOV), and maximize the field-of-regard (FOR) for each crewmember with the ability to support cost-effective reconfigurable simulators.

BACKGROUND

Different types of visual display systems have been utilized in aviation simulators. These have varied from a low cost single panel display, to multiple displays angled to provide a wider FOV, to an expensive, complex, full FOR dome. Aviators have always been the most demanding display user, requiring a 360° FOR to enable them to perform aircraft maneuvers. Pilots depend highly on their peripheral vision that cannot be simulated (or *stimulated*) by simple flat panel displays and have long complained about how hard it was to train as a unit when they couldn't rely on their peripheral vision to maintain situational awareness of other aircraft. The dome appears to solve this problem but is exponentially more expensive than single displays, and requires much more operation and maintenance support. If a single display breaks, you can simply roll it out and bring in another one. If the dome breaks, the simulator is down until it is repaired.

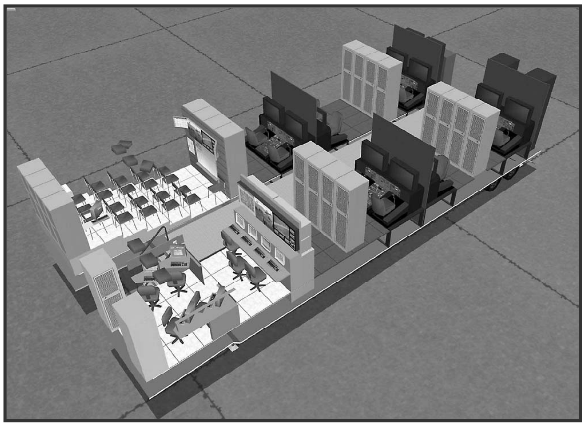
Adding in the requirements that the simulator be low cost, portable and support reconfigurable cockpits, an alternative choice for the visual display is the HMD. While HMDs have found their way into a myriad of applications, their use in aircraft simulation has been limited primarily because the fidelity of imagery required for aircraft simulation dictates a wide FOV, high-resolution, full-color image to accurately replicate the real world battlespace that is at the same time lightweight and comfortable enough to wear for long training sessions. Recent developments in computer image generator technology, head tracking, and image source technology have allowed the use of HMDs as the primary image source.

AVCATT-A

The Aviation Combined Arms Tactical Trainer-Aviation (AVCATT-A) Reconfigurable Manned Simulator is a suite of mobile, transportable, reconfigurable aviation simulators, developed as part of the Combined Arms Tactical Trainer (CATT) family. AVCATT-A is currently being sponsored by the U.S. Army Simulation, Training and Instrumentation Command (STRICOM) as an aviation collective training virtual simulation system to allow commanders achieve and sustain unit proficiency and combat readiness. As a networked system, it provides a needed collective training capability that permits units to train as units and not as individual aircrews. It also provides the capability to conduct realistic, high intensity, task loaded collective and combined arms training exercises and mission rehearsals (Simons, Schaefer & Melzer, 2002).

The physical layout of an AVCATT-A suite consists of two trailers connected by a raised, covered platform. One trailer includes three reconfigurable manned modules and a 20-person After Action Review (AAR) facility. The second trailer includes an additional three reconfigurable manned modules, a Battlemaster Control room, and a maintenance room. Thus, the AVCATT-A provides a total capability of six manned module cockpits per suite, networked together and capable of training an aviation company or air cavalry troop. Each manned module has the ability to be reconfigurable to current Army attack, reconnaissance, cargo, and utility aircraft as shown in Figure 1. As seen from the layout, space is a premium. Not only must the manned module fit into its allocated space in the trailer, but all other components that are not being utilized must be stored in the trailer during non-use. This requires the optimization of space for all the components of the manned module including the visual system.

Fig. 1 AVCATT-A suite layout showing the two trailers with the six reconfigurable cockpits and support facilities.



AVCATT-A Reconfigurable Cockpits

AVCATT-A has the ability to provide five functional cockpits with provisions for both side-by-side and tandem configurations. The first cockpits being developed for AVCATT-A are the AH-64A Apache, AH-64D Apache Longbow, OH-58D Kiowa Warrior, UH-60A/L Blackhawk, and CH-47D Chinook helicopters. An RAH-66 Comanche simulator will also be provided and is currently undergoing requirements definition. In addition to having the requirement to be reconfigurable, AVCATT-A must have all the parts required for the various configurations contained within the trailers, which eliminates the potential for roll-in/roll-out cockpits. With these constraints, the challenge for AVCATT-A was to accommodate the visual requirements for each of the cockpit configurations with a single generic hardware solution, and with as much common software as possible.

AVCATT-A Visual Requirements

The Kiowa Warrior, Blackhawk, and Chinook cockpits require that the seats be side by side whereas the Apache and – when implemented – the Comanche cockpits require that the seats be tandem. Each has unique eye points, with different flight instruments and controls. The visual system must accommodate these cockpit requirements for each aircraft while maintaining a positive training environment. The visual displays duplicate all vision path obstructions and restrictions as encountered on the real vehicle including limitations resulting from head motion and parts of own vehicle that obstruct the view, as well as a FOR and cockpit mask that is specific to each aircraft.

To satisfy the variety of visual requirements for the various aircraft, AVCATT-A's primary visual display system is the HMD. Although they have previously been utilized in aviation simulators, the AVCATT-A is unique in that *everything is being driven through the HMD*. Flat panel displays are installed in the simulator, but are covered up during operational use and only utilized if an HMD fails. The HMD provides all the Out-The-Window (OTW) views using a three-dimensional aircraft-specific mask that displays the size and shape of each cockpit to both the pilot and copilot/gunner from their respective seats. The AVCATT-A has a requirement for a total FOV of 100° horizontal by 50° vertical. The image to each eye is 65° horizontal by 50° vertical with 30° of binocular overlap. In addition, the HMD must also be capable of overlaying aircraft symbology over the OTW view, present FLIR capability, and simulate the use of night vision goggles with 6 Degree of Freedom (6DOF) head tracking to accurately present the cockpit mask.

To select an HMD that would meet the AVCATT-A visual display requirements, STRICOM conducted a Government Trade-off analysis of four existing HMDs. Visual performance evaluation criteria included the following:

- Horizontal and vertical field-of-view
- Binocular overlap
- Display resolution
- See-through transmission
- Eye Relief distance
- Exit Pupil diameter
- Image luminance
- Image contrast
- Focus and convergence distance
- Vernier adjustments for fitting and sizing
- Interpupillary distance adjustment
- Head-supported weight and balance

In addition to performance, delivery schedule and design risk were also evaluated. As a result of this analysis, a decision was made to use the Kaiser Electro-Optics SIM EYE XL 100A HMD as the primary visual display for AVCATT-A.

WHAT IS A HEAD-MOUNTED DISPLAY (HMD)?

A Head-Mounted Display (HMD) is a personal information-viewing device mounted on the head that can provide information in a way that no other display can. The imagery is continuously projected into the user's eyes and it can be made reactive to head and body movements, replicating the way we view, navigate and explore the world.[1] This unique capability lends itself to applications such as Virtual Reality for creating artificial environments (Kaslawsky, 1996), medical visualization as an aid in surgical procedures (Schmidt & Osborn, 1995, Pankratov, 1995), military vehicles for viewing sensor imagery (Casey, 1999), airborne workstation applications reducing size, weight and power over conventional displays (Browne, 1998), fixed and rotary wing avionics display applications (Foote, 1998, Belt, Kelley & Lewandowski, 1998) and aircraft simulation and training (Lacroix & Melzer, 1994, Casey & Melzer, 1991, Thomas & Geltmacher, 1993).

In some applications, such as the medical and soldier's displays, the HMD is used solely as a hands-off information source. To truly reap the benefits of the HMD as part of a simulation application such as AVCATT-A, however, it must be part of a Visually Coupled System (or VCS) that includes the HMD, a head position tracker, and a computer image generator (Kocian, 1987, Rash, 1999). As the pilot or trainee turns their head, the tracker relays the orientation data to the image generator, which updates the visual imagery accordingly. This gives the pilot a myriad of real-time data that is *linked to head orientation*. The reduced size of the HMD over the traditional dome simulator means that the training system is smaller, less costly and the entire suite can be deployable.

There are numerous HMDs currently on the market. As presented in a recent HMD survey ("Annual Survey", 2001), HMDs range from devices that are worn like sunglasses, to ones that are integrated with helmets, to ones that are freestanding that you lean forward and look into. They range from relatively simple devices that are used by the gaming market, to high fidelity systems that are used to drive the visual scene for a military simulator. The HMD used on AVCATT-A meets program requirements for total FOV with stereoscopic capability, XGA resolution (1024 pixels by 768 lines), full color active matrix liquid crystal device (AMLCD) image sources (3.8 arc minutes per color group), with a target weight of less than 7 pounds.

The Original Wide Eye™

The predecessor to the SIM EYE HMD is the Wide Eye™ *helmet*-mounted display. As a result of the success of the IHADSS (30° x 40° monocular FOV, monochrome) on the AH-64 Apache helicopter (Belt, Kelley & Lewandowski, 1998), the US Army required that an HMD be part of the avionics suite for the Light Helicopter Experimental (LHX) program.[2] The result was the Wide Eye™ HMD, which was baselined into the aircraft as shown in Figure 2.

Fig 2. The original Wide Eye™, the predecessor to the SIM EYE.

One of the key features of this design was the two part helmet approach: A custom-fitted helmet for the pilot (the Pilot Retained Unit or PRU) with the more expensive display hardware mounted on a lightweight, carbon-graphite frame that stayed in the aircraft (the Aircraft Retained Unit or ARU). The two 40°monocular display assemblies were mounted on either sides of the U-shaped ARU to provide binocular imagery, each with a miniature high brightness, monochrome CRT as the image source (Sauerborn, 1992). The ARU frame's stiffness maintained the critical binocular alignment (Moffitt, 1997) between the two optical relay assemblies while allowing a smooth lateral adjustment for interpupillary distance. To expand the horizontal field of view, the monoculars were canted outward using partial binocular overlap (Melzer & Moffitt, 1991, Melzer, 1998). This provided a total binocular field of view of 40° vertical by 60° horizontal with 20° of central binocular overlap. Several of these features, including the two part configuration (separate helmet and binocular assembly), and the use of partial binocular overlap are still part of the SIM EYE XL100A.

[1] The term Head-Mounted Display is used in this paper as a more generic term than *Helmet*-Mounted Display which most often refers to military-oriented hardware.

[2] The LHX program has since become the RAH-66 Comanche helicopter program.

The First SIM EYE

Recognizing the need for a HMD for non-flight applications, the Wide Eye™ was converted to a design that would support simulation and training. The first version was the Simulation Eye 2500 or SIM EYE 2500, produced in 1992. The optical design was very similar to that of the Wide Eye™, using a monochrome (green) CRT, and a dual reflective combiner eyepiece with a two-piece helmet specifically designed for simulation applications. The SIM EYE 2500 provided a similar 40° x 60° field of view, the same 15 mm exit pupil and 31 mm eye relief as the Wide Eye™, with a reduced display luminance as shown in Figure 3.

Fig 3. The SIM EYE 2500

In 1993, the SIM EYE 2500 was converted to a color display using field-sequential video[3]. The field of view of the SIM EYE 40 was similar to that of the SIM EYE 2500, with adjustable display luminance in the 15-20 fL range and 1024 video line resolution. To provide immersive imagery for simulation and training required an increase in the FOV. The dual reflective combiner design becomes unacceptably large at about 45°, leading to an alternative eyepiece concept, called the Vision Immersion Module or VIM™ (Berman and Melzer, 1989). The compact nature of the VIM™ and the high transmission makes this an ideal candidate for the eyepiece. The result was the SIM EYE 60 as shown in Figure 4. Note that the 60° VIM™ eyepiece is the same size as the 40° dual reflective combiner used in the SIM EYE 40 as shown in Figure 4. With adjustable binocular overlap, the SIM EYE 60 was capable of providing 60° circular (with 100% overlap), 60° x 80° (40° binocular overlap), or 60° x 100° (20° binocular overlap).

Fig 4. The SIM EYE 60

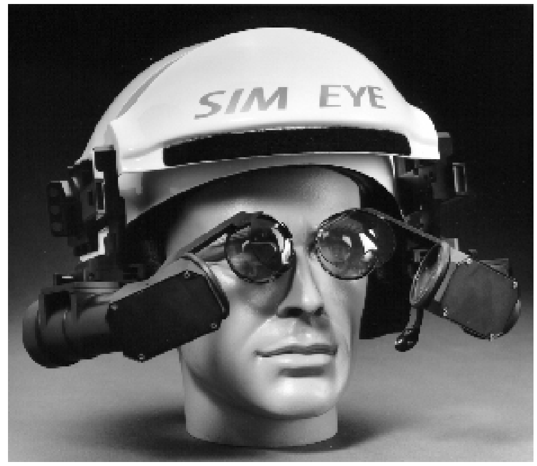


Image source technology improvements mean better performance

In 1999, the SIM EYE was upgraded to exchange the CRTs for XGA resolution transmissive LCDs. The result was the SIM EYE XL100. The crisp imagery from the LCDs provided a significant improvement over the CRT imagery, plus, using *color addition* versus *field sequential color* (Post, 1994) reduced the perceptual artifacts such as color breakup with fast-moving objects. This system maintained the same binocular overlap adjustments as on the SIM EYE 60. Each monocular provided a 64° horizontal by 46° vertical FOV. Adjustable partial binocular overlap provided four different horizontal field of view settings ranging from 64° (100% overlap) to 108° (20° binocular overlap).

Figure 5 shows the LCD-based SIM EYE XL100

[3] 60 Hz video is frame-buffered and the red, green and blue constituents of the image are displayed sequentially at 3 times the video rate or 180 Hz.

The AVCATT-A HMD

The latest version of the SIM EYE is the XL100A (see Figure 6), so designated because it retains the features of the original XL100 system with some improvements in performance. The field of view fixed at 50° x 100° with 30° binocular overlap. Resolution is 3.8 arcminutes with the full-color XGA video resolution, but the display luminance is increased to 20 fL. Improvements in the cholesteric reflector for the VIM™ provide an increased see-through transmission of >20%.

Fig 6. SIM EYE XL100A

The SIM EYE XL100A has gone through extensive evaluation by users during the various AVCATT-A Build tests. Recognizing the value of a HMD for the primary visual display, their comments have been instrumental in ensuring that the HMD meets the visual requirements for AVCATT-A. Some of the feedback received from the user is as follows:

- "Good FOV."
- "Good visibility, ability to look around aircraft struts and to the sides of the aircraft."
- "Makes flying the simulator more like flying in the real aircraft, not limited to the visibility provided on flat panel displays."
- "Weight is a factor, especially when going into a Heads Down mode in the AH-64A/D."
- "LCD technology in HMD is not as crisp as CRT technology in secondary displays."
- "Image blur seems to be a problem with the HMDs."
- "60Hz update rate must be maintained. Dropping under 60Hz enhances (image) stepping in the HMD."
- "Good fit is a must to keep the optics in the "sweet spot.""
- "The bright image makes the scene illumination more difficult to obtain." (Complaint was that moonless night was not dark enough, the result of incorrectly driven video.)

DESIGN IMPROVEMENT STUDY

HMD users, especially those using them for simulation and training, require a high level of image quality to provide a realistically persuasive scenario. Wide FOV imagery supports the illusion of self-motion, balance and orientation. In viewing an increasingly larger FOV, the user crosses a barrier between *looking at* the display to *being in* the display. In simulation or virtual reality applications, this said to be "immersive" or to provide a sense of "presence." (Loomis, 1992). Humans perceive their environment through a pair of visual receptors that provide a total horizontal field of view of greater than 180° with point source acuity of 1 arc minute in the central foveal region. Since the AVCATT-A simulator relies on the HMD to provide *all* imagery to the pilot/trainee – including the OTW visuals – training fidelity depends on display performance features such as FOV, resolution and responsiveness. As the first Army aviation simulator program to use HMDs as the primary visual system, they came under intense scrutiny not usually endured by normal display systems.

Though satisfying the visual requirements in the early stages of the program, user feedback identified key areas for improvement in HMD performance to ensure that it can support lengthy simulation and training exercises. Based on these recommendations, a helmet study contract was awarded to look at improvements in specific areas. Once completed, the results will be analyzed examined for incorporation into the AVCATT-A HMD. The following three areas were targeted for investigation:

1) <u>Head supported weight</u> – The current head supported weight for the SIM EYE XL100A as it is used in the Lot 1 AVCATT-A trainer is approximately 6.5 lb. This includes the helmet shell, the two display monoculars and the 6 Degree of Freedom (6DOF) head orientation tracker. Lot 2 total weight was reduced to 5.7 lb, but further reductions are desired (and possible).

2) <u>Display resolution</u> – Increasing the display resolution of the individual display modules from the current XGA (1024 horizontal pixels by 768 vertical lines) to SXGA resolution (1280 horizontal pixels by 1024 vertical lines) will provide a better sense of realism for the trainee in the simulator and can therefore improve training effectiveness. An examination will be done to determine availability

(and compatibility) of new image source technologies.

3) Display latency – Latency or lag in an HMD-based system is typically associated with the time between when the user moves their head to when the imagery catches up. System latency includes tracker latency, data packet transfer delay, and image generator delay. Specific to the HMD is the switching speed of the liquid crystal material in the LCD image sources. The latency manifests itself as a contrast reduction or blurring when the user turns their head or when the imagery moves quickly (Rabin and Wiley, 1995). The task is to examine the response time of the baseline image sources and compare their response to that of new candidate image source technologies.

Reduction of head-supported weight

Initial user feedback indicated that head-supported weight is the highest priority item for improvement. The trade study indicated two key weight reduction areas:

Head tracker - The AVCATT-A head tracker is mounted on the top of the SIM EYE XL100A helmet as shown in Figure 7. This is a 6DOF tracker that uses a combination of gyros and accelerometers to determine head orientation angles (α, β, γ) and an ultrasonic system to measure position (x, y, and z). It should be noted that the weight of the current head tracker is compounded by its location on the top of the head, above the location of the head center of gravity,[4] which can contribute to the a top-heavy feel.

Figure 7 shows the current 6DOF head tracker for the AVCATT-A program located on top of the SIM EYE helmet.

[4] The head center of gravity location is at the tragion notch, above the cartilaginous notch in front of the ear canal (Rash, 1997).

The current head tracker is based on an older technology with form factor was dictated by the 6 inch length of the processor electronics board. Three microphones on each end were required to provide adequate coverage for the incoming ultrasonic signals with sufficient left/right separation to provide the required accuracy. There have been significant design improvements that resulted in the new *MiniTrax*. Microphone coverage has been improved to the extent that only a single one on each end is required. The electronics board has been shortened to 2 inches in length, though the microphone separation needs to be maintained at the same distance as the previous tracker. This design is referred to as the *High Accuracy MiniTrax*. It maintains the same overall length, but with a significantly reduced profile and a weight reduction of 5.4 ounces or 0.34 lb.

Optical design - To further reduce weight, a preliminary analysis was conducted on the optical design decreasing the eye relief distance from 30 mm to 25 mm and reducing the exit pupil diameter from 15 mm to 12 mm diameter. A reduction in the lens diameter results in a reduction in the overall lens volume, with a decrease in head-supported weight. In addition, the smaller exit pupil diameter reduces the speed (f-number) – and size – of the relay optics. This would result in a weight reduction as well as a potential cost reduction.

These analyses were combined with two of the other Trade Study Tasks, switching to a higher resolution SXGA LCD with a faster response time. Though not fully optimized, it appears that at least 100 grams (50 grams per side) can be removed. With some further optimization, an additional 10 – 20 grams per side in the optical design and an additional 16 – 20 grams in the mechanical housings can also be removed. It is also possible that the smaller LCD and backlight would save a few grams. Incorporating these weight reductions in the SIM EYE XL100A would remove a total of approximately 0.3 lb.

Weight reduction summary - Controlling weight during the HMD design process is a serious challenge and is best accomplished using an iterative approach. As envisioned herein, a combination of changes to the 6DOF head tracker and the SIM EYE XL100A could result in an overall head-supported weight reduction of approximately 1.42 lb could be realized. A comparison table is shown below:

Lot	SIM EYE XL100A weight	Head tracker weight	Total head supported weight	Comments
Lot 1	6.08 lb	.42 lb	6.50 lb	Lot 1 HMD with existing head tracker
Lot 2	5.3 lb	.42 lb	5.72 lb	Lot 2 lightweighted HMD with existing head tracker
"Lightweight Version"	5.0 lb	.08 lb	5.08 lb	Improved optical, mechanical design, High Accuracy MiniTrax head tracker

Increasing Display Resolution

Designers and users of HMDs want display systems with visual performance that approaches human vision, but have been limited up until recently by the availability of high resolution image source technology. The SIM EYE XL100A currently uses three monochrome (red, green and blue) transmissive XGA LCDs. At the time the SIM EYE XL100A was designed, these were the highest resolution devices available. Since that time, however, there have been new, higher resolution (SXGA - 1280 horizontal pixels by 1024 vertical lines) devices introduced into the market. In this part of the trade study, we considered the impact of upgrading the resolution, taking into consideration the issues of size, weight, power, transmission, aspect ratio, color, and optical performance. Two primary candidates are under consideration: a high performance transmissive LCD designed primarily for high-end military display applications (Woodard, Gale, Ong, & Presz, 2000), the other a high-end commercial reflective LCD.

It is important to note that the aspect ratio changes from the XGA (4:3) to SXGA (5:4). Thus, the optical design (and image generator data base) must be capable of handling the smaller pixel size as well as the change in overall aspect ratio. As mentioned in the previous section, the transmissive candidate offers fast response time as well as the opportunity to reduce the overall size (and subsequently the weight) of the relay optics.

Display latency

Image latency or lag in with a simulation system can have results that range from a minor annoyance (from color shift or reduction in resolution) to a reduction in training transfer (from serious lack of synchrony of head motion with image motion). *System lag* can be traced to a number of system parameters such as head tracker latency, slow transfer of data packets from the head tracker to the image generator, poor handoff of the data within the image generator, or slow update rate of the image generator itself.

LCDs (such as those used in the SIM EYE XL100A) are constructed of two parallel plates of conductive glass with liquid crystal material within the gap. In the relaxed state, the oblong molecules align themselves in the rubbing direction so they rotate 90° from one plate to the other and light passes through the pixel (clear state). When a voltage is applied, the molecules align themselves in the direction of the electric field, and the crossed polarizers block light (black state). Gray scale is created by applying a reduced voltage to the gap. The transition from the clear to black state is typically faster than the transition from black to clear due to the viscosity of the material. It is this transition time that is the key to the LCD response time. A slow response in either direction will manifest as a contrast reduction or blurring when the user turns their head or when the imagery moves quickly. Although the AVCATT-A system passed the "sharpness" requirement, there is room for improvement to reduce the perceived change in image quality during head movement. When originally designed, the SIM EYE XL100A used high performance commercial projection LCDs that were optimized for transmission and contrast, though not necessarily response time. Since then, the industry has moved towards faster devices to support the growth of video projection. These newer devices, the aforementioned high-end transmissive LCD and a reflective (ferroelectric) device will be examined to determine their gray scale-to-gray scale transition time, in the interest of reducing display image latency.

SUMMARY

As the first Army aviation simulator to utilize HMDs in the role of primary visual display, AVCATT-A has had to meet the challenge of high user expectations. The aviator has always stated that their desire for the display FOV and resolution should be as though they were looking outside the actual aircraft – expectations that the AVCATT-A HMD is striving to meet. Extensive testing shows that the first AVCATT-A HMDs meet their baseline performance requirements and feedback from the user community has indicated that flying the AVCATT-A simulator is more realistic with the HMD than with flat-panel secondary displays, although improvements can be made. As the AVCATT-A HMD continues to develop, these improvements will be implemented to produce a HMD that the Army aviation community will embrace.

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