3 INTRODUCTION TO HELMET-MOUNTED DISPLAYS

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In order to fully understand the sensory, perceptual, and cognitive issues associated with helmet-/head-mounted displays (HMDs), it is essential to possess an understanding of exactly what constitutes an HMD, the various design types, their advantages and limitations, and their applications. It also is useful to explore the developmental history of these systems. Such an exploration can reveal the major engineering, human factors, and ergonomic issues encountered in the development cycle. These identified issues usually are indicators of where the most attention needs to be placed when evaluating the usefulness of such systems.

New HMD systems are implemented because they are intended to provide some specific capability or performance enhancement. However, these improvements always come at a cost. In reality, the introduction of technology is a tradeoff endeavor. It is necessary to identify and assess the tradeoffs that impact overall system and user sensory systems performance. HMD developers have often and incorrectly assumed that the human visual and auditory systems are fully capable of accepting the added sensory and cognitive demands of an HMD system without incurring performance degradation or introducing perceptual illusions. Situation awareness (SA), essential in preventing actions or inactions that lead to catastrophic outcomes, may be degraded if the HMD interferes with normal perceptual processes, resulting in misinterpretations or misperceptions (illusions).

As HMD applications increase, it is important to maintain an awareness of both current and future programs. Unfortunately, in these developmental programs, one factor still is often minimized. This factor is how the user accepts and eventually uses the HMD. In the demanding rigors of warfare, the user rapidly decides whether using a new HMD, intended to provide tactical and other information, outweighs the impact the HMD has on survival and immediate mission success. If the system requires an unacceptable compromise in any aspect of mission completion deemed critical to the Warfighter, the HMD will not be used. Technology in which the Warfighter does have confidence or determines to be a liability will go unused.

Defining the Helmet-Mounted Display

Melzer and Moffitt (1997) describe an HMD as minimally consisting of "an image source and collimating optics in a head mount." From the perspective of U.S. Army rotary-wing aviation, Rash (2000) extended this description to include a coupling system that uses head and/or eye position and motion to slave one or more aircraft systems, typically a head-directed sensor. Using this description, Figure 3-1 presents a basic block diagram in which there are four major elements: image source (and associated drive electronics), display optics, helmet, and head/eye tracker. The *image source* is a display device upon which sensor imagery is reproduced. Early on, these sources were miniature cathode-ray-tubes (CRTs) or image intensification (I^2) tubes. More recently, miniature flat panel display technologies have provided alternate choices. The *display optics* is used to couple the display imagery to the eye. The optics unit generally magnifies and focuses the display image. The *helmet*, while providing the protection for which it was designed originally, also now serves as a platform for mounting the image source and display optics. The *tracking system* couples the head orientation or line-of-sight with that of the pilotage sensor(s) and weapons.

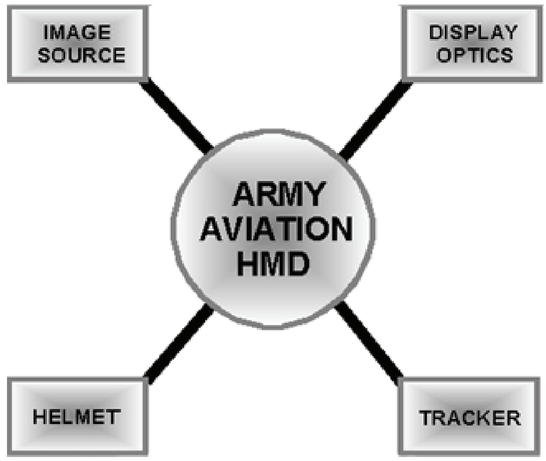

Figure 3-1. Block diagram of a basic U.S. Army rotary-wing aviation HMD.

However, this extended description of HMDs is still limited by its close association with use in military rotary-wing aircraft as well as being focused only on the visual system. Manning and Rash (2007) provide a more generalized description of visual HMDs that is applicable to both military and commercial applications, where the name "head-worn displays" (HWDs) has been gaining acceptance. The same basic four building blocks are employed but are expanded in scope:

- A *mounting platform*, which can be as simple as a headband or as sophisticated as a full flight helmet. In addition to serving as an attachment point, it must provide the stability to maintain the critical alignment between the user's eyes and the HWD viewing optics;
- An *image source* for generating the information imagery that is optically presented to the user's eyes. Advances in miniature displays have produced a wide selection of small, lightweight and low-power choices at moderate cost, while meeting the demands of perceptual intensity and resolution (See Chapter 4, *Visual Helmet-Mounted Displays*.);
- *Relay optics*, which transfer to the eye(s) the information at the image source. Relay optics typically consists of a sequence of optical elements (mostly lenses) that terminates with a beam-splitter (combiner). Initial designs for visual applications were monocular with a single beam-splitter in front of one eye, but as miniature display technologies develop, binocular designs are becoming dominant;[1] and,
- A *head-tracker*, which is optional if the HWD is used only to present status information using non-spatially-referenced symbols. However, it often is required if external (outside) imagery is supplied by a sensor or a synthetic database. If such imagery is to be presented, the user's directional line-of-sight must be recalculated continuously (updated) and used to point the sensor or to select the synthetic imagery data correlated with the user's line-of-sight. Presentation of head-referenced information (imagery and/or symbology) via a head tracker requires a preflight calibration procedure called boresighting, which aligns the sensor's and user's lines-of-sight.

Each of these fundamental HMD building blocks has engineering, sensory, perceptual, cognitive, and ergonomic considerations that will be explored in future chapters. All of these engineering and human factor

[1] For the audio realm, three-dimensional (virtual) audio technologies are being developed. Tactilely, small vibrators are being explored for 360 degree enhanced awareness.

considerations are interrelated; therefore, tradeoffs are required in order to achieve a design that will be functionally acceptable for a specific operational application. As the tradeoffs are implemented, it is essential that the developer and the user be aware of the performance implications of these tradeoffs. The following sections will use the visually based HMD as an example of these considerations.

Classifying Visual Helmet-Mounted Display Designs

Since visual HMDs are complicated systems, there are several classification schemes that can be employed. These include those based on image source, image display technology, imagery presentation mode, and optical design approach. The image formed by an optic system, e.g., an HMD, can be real or virtual. At a practical level, the image is real if the light rays to be focused by the eye or a camera are spreading farther apart, i.e., diverging. This is the case when we view a real object directly or in a flat mirror, a photograph, the screen at a movie theater, or view an image focused by a convex lens from beyond its focal plane. The image formed is outside the optical system; the light rays (or wave front) from the image points that reach the eye are diverging. An image is virtual if the light rays to be focused by the eye are moving closer together, i.e., converging. Examples of virtual images include those from telescopes or microscopes focused by the user, a real scene viewed through a concave lens, or looking into a convex lens from a point inside its focal plane.

Real-image HMD designs are rare. A direct-view image source like a miniature liquid crystal display (LCD) would have to be located no closer than reading distance, which is not practical. Putting the appropriate optics in front of the miniature display to move it closer to the eye would likely make the image virtual. All currently fielded HMDs are set to produce virtual images (although a slightly diverging system than produces some accommodation in the eye for presented symbology while viewing a real scene through the display may have some attentional advantages).

Virtual image displays offer several advantages (Seeman et al., 1992). At near optical infinity, virtual images theoretically allow the eye to relax (reducing visual fatigue) and provide easier accommodation for older users. By providing a virtual image, a greater number of individuals (but not all) can use the system without the use of corrective optics. A collimated image also reduces effects of vibration that produces retinal blur.

Shontz and Trumm (1969) categorize HMDs based on the mode by which the imagery is presented to the eyes. They define three categories: One-eye, occluded; one-eye, see-through; and two-eye, see-through. In the *one- eye, occluded* type, imagery is presented to only one eye, to which the real world is blocked, with the remaining eye viewing only the real world. The *one-eye, see-through* type, while still providing imagery to one eye, allows both eyes to view the real world. (Note: The optics in front of the imagery eye will filter the real world to a lesser or greater degree.) The Integrated Helmet and Display Sighting System (IHADSS)[2] employed on the AH-64 Apache helicopter is an example of this type. In the *two-eye, see-through* type, imagery is presented to both eyes, while the real world also is viewed by both eyes.[3] The Thales TopOwl™ is an example of this type.

Another classification scheme, which parallels the three types described above, uses the terms monocular, biocular, and binocular. These terms refer to the presentation mode of the symbology and/or sensor imagery by the HMD. For our usage, *monocular* means the HMD sensor imagery is viewed by a single eye; *biocular* means the HMD provides two visual images from a <u>single</u> sensor or multiple sensors, but each eye sees exactly the same image from the same perspective; *binocular* means the HMD provides two visual images, one for each eye, from two sensors displaced in space, thus providing perspective. (Note: A *binocular* HMD can use a single sensor, if the sensor is manipulated to provide two different perspectives of the object scene.) Both *biocular* and *binocular* HMDs will have two optical channels (one for each eye). Note that a two-eyed HMD presenting *biocular* imagery

[2] The IHADSS system now is owned and manufactured by Elbit EFW, Fort Worth, TX.
[3] Not included in this classification scheme is a “two-eye, occluded” category such as Night vision Goggles (NVGs)

from one sensor/database is still capable of presenting *binocular* symbology overlays as long as it has two independently controllable image sources

Typically, binocular HMDs use optical designs that fully overlap the images in each eye. In such HMDs, the field-of-view (FOV) is limited to the FOV of the display optics. However, in order to achieve larger FOVs, recent HMD designs partially overlap the images from two optical channels. This results in a partially-overlapped FOV consisting of a central binocular or binocular region (simultaneously seen by both eyes) and two monocular flanking regions (each seen by one eye only) (Figure 3-2). Such overlapping schemes can be implemented by either divergent or convergent overlap designs. In a divergent design, the right eye sees the central overlap region and the right monocular region, and the left eye sees the central overlap region and the left monocular region (Figure 3-3a). In a convergent design, the right eye sees the central overlap region and the left monocular region, and the left eye sees the central overlap region and the right monocular region (Figure 3-3b).

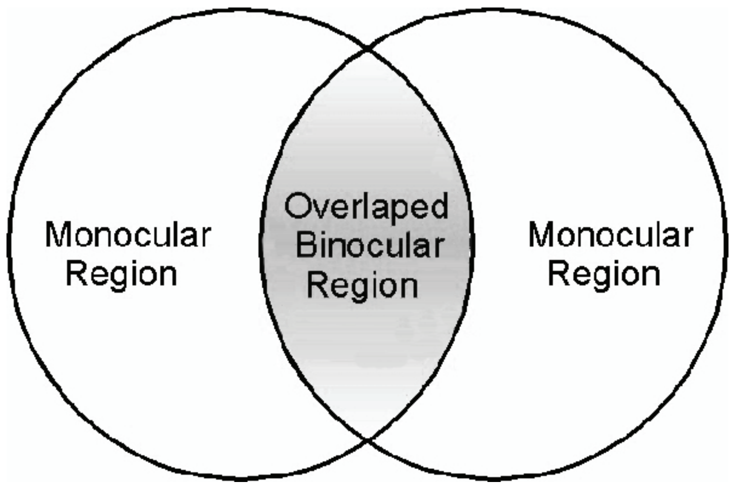

Figure 3-2. Partially overlapped FOV with a central binocular region and two monocular regions

The IHADSS is an example of a monocular HMD; the Aviator's Night Vision Imaging System (ANVIS) is an example of a 100% overlapped binocular HMD; and the Kaiser Electronics' CRT-based Helmet Integrated Display Sight System (HIDSS) design is divergent and has an overlap of approximately 30% (based on a 17º overlap region within the 52º horizontal FOV).

Classifying HMDs by optical design is even more complicated. The simpler and more predominant types use optical designs based on reflective and refractive lens elements that relay the HMD image source to the eye. A standard characteristic of these designs is the presence of a final partially-reflective element(s) positioned in front of the user's eye(s) called "combiners" (Wood, 1992). These elements combine the see-through image of the real world with the reflected image of the HMD image source. Reflective/refractive optical designs will be discussed in detail in Chapter 4, *Visual Helmet-Mounted Displays*.

Another HMD type is based on a visor projection design (e.g., Cameron and Steward, 1994). A simple diagram of this design approach is presented in Figure 3-4. The image source(s) is usually mounted around (top/side) the helmet, and the image is relayed optically so as to be projected onto the visor where it is reflected back into the user's eye(s). The advantages of visor projection HMDs include lower weight, improved center-of-mass (CM), increased eye relief, and maximum unobstructed visual field. A possible deficiency is image degradation that can result in a high vibration environment. An optical problem that can show up with this design is the production of ghost images. Also, this design requires that the visor be able to be placed consistently at the same position. Recently, visor projection designs have been revisited (Chapter 4, *Visual Helmet-Mounted Displays*).

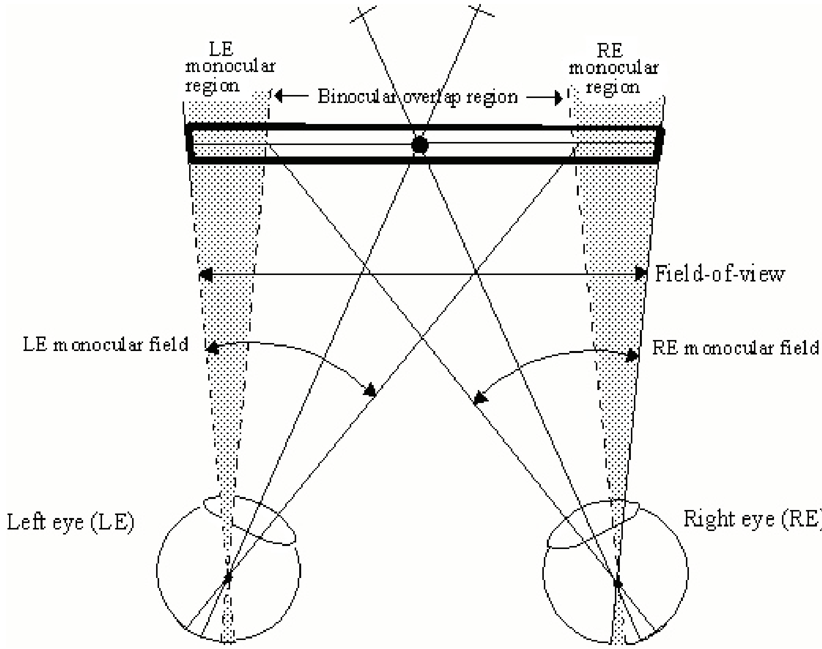

Figure 3-3a. Visual interpretation of the divergent display mode.

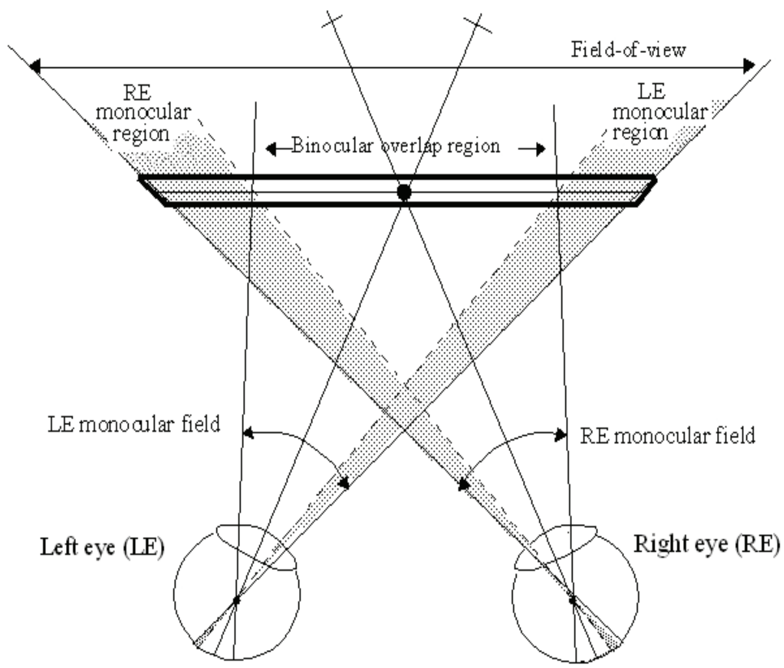

Figure 3-3b. Visual interpretation of the convergent display mode.

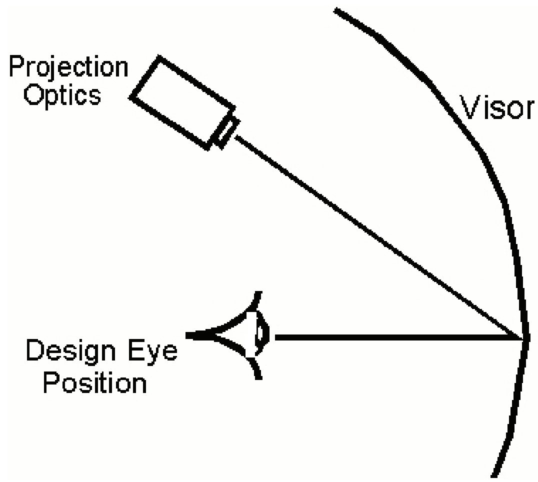

Figure 3-4. Visor projection HMD design approach.

Another approach, which again allows for low weight and provides a compact design, is one using holographic optical elements (Vos and Brandt, 1990). A holographic combiner is used to merge the standard combiner function with the collimation function usually performed by an additional refractive optical element. This merging implies that the holographic combiner acquires optical power, hence the term *power combiner* (Wood, 1992). In some designs, the visor serves as the combiner, with a holographic coating on the visor substrate. Disadvantages of this approach include the problem of preventing humidity and temperature effects from degrading the holograms. Considerable progress has been made in mitigating these problems in the last few years.

One of the most recent entries into HMD design approaches is the use of lasers that scan an image directly onto the retina of the user's eye (Johnston and Willey, 1995). Figure 3-5 provides a diagram of the basic retinal scanning approach. This approach eliminates the need for a CRT or flat panel (FP) image source, offering the potential of improving both weight and CM. Other cited advantages of this system include diffraction (and aberration) limited resolution, small volume (for monochromatic), full color capability, and high brightness potential. Disadvantages, at least potentially, include scanning complexity, susceptibility to high vibration environments (as with helmet slippage in military environments), limited exit pupil size, and safety concerns.

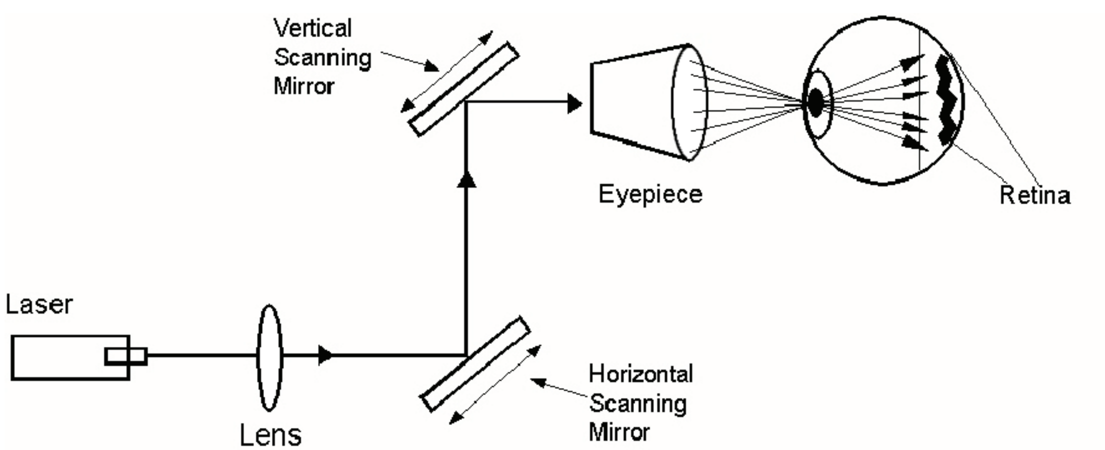

Figure 3-5. Basic diagram of retinal scanning display (adapted from Proctor, 1996).

A recent optical design for HMDs developed by BAE Systems uses wave-guide technology. This system uses holographic optics embedded between two transparent plates to direct the image to the eye. The potential advantages to this system are simplicity, large eye relief, ability to use in conjunction with existing night vision goggles (NVGs), lower cost, reduced weight and ability to adapt to existing military helmets. Although most of the disadvantages are unknown at this time, safety related to the plate placed in front of the eye and the eventual FOV have not been fully addressed. This approach is used in BAE System's Q-Sight™ HMD discussed in the *Current and Future HMD Programs* section of this chapter.

Regardless of the actual optical approach used, a visual aviation HMD also must include an image source, a head/eye tracker (if sensor is remotely located), and a helmet platform. At one time, the traditional approach was to integrate the optics and image source into a subsystem which was then mounted onto an existing helmet (Melzer and Larkin, 1987). This after the fact add-on approach was used with ANVIS. As one might expect, attaching one subsystem to another subsystem may not produce the optimal design. Instead, an integrated approach in which all elements and components of the HMD are designed in concert generally will result in the best and most functional overall design. The IHADSS was the first HMD product of the integrated approach, i.e., the helmet and the HMD optics were developed as a system, even though the optics is a removable component.

Even when using an integrated approach, the desired application of an HMD will impact design, leading to a variety of configurations. There is no one-design-fits-all scenario. In fact, the various missions, and the conditions under which they must be performed, are so different, that a single HMD design, while optimal for one set of conditions, may be significantly deficient for other mission scenarios. A solution to this problem may be a modular approach (Bull, 1990), where the HMD system consists of a base mounting unit (e.g., helmet platform), and interchangeable modules that can be attached, each for a specific set of mission requirements. This modular approach can be effective as long as an integrated approach is used that does not compromise the basic requirements of any subsystem. For example, the helmet, while now being used as a platform to attach optics, still must serve its primary functions of providing impact, visual, and acoustical protection. The HIDSS HMD design for the now cancelled U.S. Army Comanche program was an example of the modular approach.

The visually-coupled system (VCS) concept

Head-position sensing or head tracker technologies provide the pilot's/operator's "caged eyeball" line-of-sight as a control input to the aircraft/vehicle and its on-board sensors and weapons. This class of head-mounted system has sometimes been called a helmet-mounted sight. HMD technologies provide virtual image display capability integral to the user's helmet. When combined, they form a class of systems many times referred to across the military community as VCS, as illustrated in Figure 3-6. With closed loop VCS, the head tracker technology serves as the control path input to sensors, weapons, avionics, or the vehicle itself, while the HMD technology provides the display symbology/imagery feedback. It should be noted that even the most basic head tracker requires at least a simple display reference a "crosshair" or "reticle" so the user knows what line-of-sight is being sensed. It is also worth noting that the image intensification technology (commonly referred to as NVGs) that has evolved over this same timeframe represents a "self-contained" VCS, in that NVGs present spatially-referenced image intensification information to the wearer.

VCS take advantage of the psycho-motor skills of the operator to provide an intuitive visual interface to the vehicle, its on-board systems, and the surrounding environment. VCS provide a "look-and-shoot" vs. a "point-the-vehicle-and-shoot" capability for effective targeting of airborne and ground, and stationary and moving ground targets. This class of systems provides an expanded off-axis visual capability for the entire range of mission requirements. As time has gone on, there has been an increase in situations where the individual Warfighter is the "weapon platform" of choice with rapid adaptability and real-time decision-making before the enemy can react. Human systems, and in particular, visually-coupled display systems, optimize and sustain the human role in combat operations.

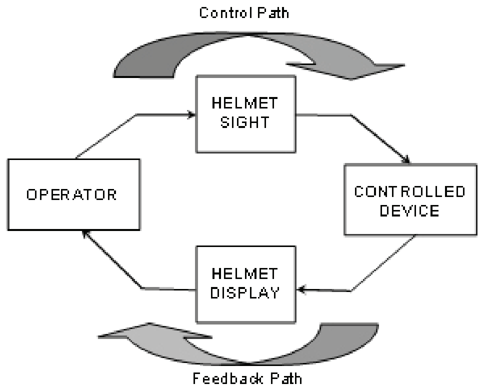

Figure 3-6. Visually-coupled system concept block diagram.

The History of Helmet-Mounted Displays

The official history of HMDs starts almost a century ago, with Albert Bacon Pratt, of Lyndon, Vermont. During the height of World War I, between 1915 and 1917, Pratt was awarded a series of U.S. and U.K. patents (Marshall, 1989), for an "Integrated Helmet Mounted Aiming and Weapon Delivery System" for a marksman (Figure 3-7).

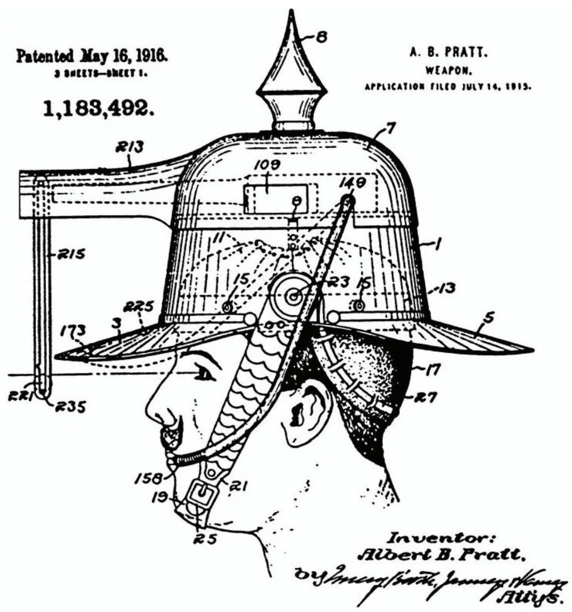

Figure 3-7. Albert Pratt's helmet-mounted display (Marshall, 1989).

Pratt, a chemical engineer, claimed a few features in his patent that have survived through the years and are as valid today as they were 100 years ago. A couple of comparisons between Pratt's patent claims and features of today's HMD designs will help establish his design as the precursor of current HMDs.

- Size and Fit

"The helmet preferably will be made in two sizes, a large size and a small size. To adapt the helmets to fit different size heads the lower section is provided with flexible linen."

Today's flying helmets are designed in small, medium, large and extra large sizes; the liner is customized to individual pilots.

- Target Acquisition

"The gun is automatically aimed unconsciously to the turning of the head of the marksman in the direction of the target. In self-protection one instinctively turns the head in the direction of attack to see the enemy. Thus, the gun is automatically directed toward the target."

Today's HMDs embody the same "look-and-shoot" philosophy; sophisticated technology with Kalman filtering tracks the instantaneous pilot's line-of-sight to guide missiles to the target.

- Dual Use

On a lighter note, the crown of Pratt's helmet (Item #7) doubled as a cooking pan, with the gun barrel safeguard (Item #213) serving as the handle. Whereas some might think the top spike (Item #8) is intended for hand-to-hand combat, it is simply stuck into the ground to support the pan while dining in the field.

Also, despite conducting an in-depth literature research, the authors of this chapter were not able to identify a like-functionality for modern helmets.[4] Advantage, Pratt!

The concept and the potential applications of HMDs in aircraft cockpits have fascinated military aviation strategists for decades. The idea of placing a virtual image focused at infinity in the visual path of the pilot and overlaying computer-generated images so that mission critical information is always available with "eyes-out," has mobilized incredible technical and financial resources over the last decades. It is generally acknowledged that an HMD, when part of a Visually Coupled System (VCS), is among the most valuable visual aids in the arsenal of a military pilot. Experience has shown that nothing can be added to a tactical aircraft that give more "bang for the buck" or operational payoff-per-pound-added than a VCS.

Military HMD development: historical overview

The various militaries across the world have actively pursued the research, development, application, and fleet introduction of a variety of helmet-mounted technologies for over forty years. A complete overview of the HMD technology development over the last forty years would be difficult as there have been hundreds of head tracker and HMD development efforts. Additionally, in recent years the concept of virtual reality has spurred interest in HMDs within industry and the general population. One artifact of the vast interest in HMDs has been the failure of the military (and more recently the commercial) communities to develop and accept an overall plan that would establish unambiguous guidelines for HMD development, not that such efforts have not been attempted.

Within the U.S., in 1995 (Brindle, Marano-Goyco, and Tihansky, 1995) under the auspices of a Tri-Service Working Group reporting to the Office of the Undersecretary of Defense for Research and Engineering, a technology-development taxonomy was established to help the HMD community properly categorize and

[4] The modern plastics-composite helmet has lost considerable functionality, as the early steel-pot was used to cook, wash, dig, etc.

articulate the diverse spectrum of research and development (R&D) programs underway at any point in time. The taxonomy's main categories included:

- *Human System Integration*, dealing mostly with efforts on safety, anthropometry, vision, situation awareness, spatial disorientation, symbology, and audio performance/hearing protection.
- *Component Development*, focusing on optics, image intensification, head trackers, image sources, three-dimensional (3-D) audio, and voice recognition; interconnect technology/ systems, and symbol generation/graphics.
- *System Development* for air and ground vehicles, the individual warrior, and simulation.
- *System Integration and Analysis*, coordinating all R&D efforts dealing with a) helmet system integration – both the integration of the various VCS components with each other and with existing personal life support equipment; and b) vehicle/laboratory system integration for properly integrating the helmet-mounted system with the vehicle and the vehicle sensors/weapons/subsystems.
- *Application Demonstration/Measurement and Evaluation*, oriented toward laboratory measurements, simulation evaluations, flight-worthiness testing, flight evaluations, concept demonstrations and field trials.

In order to highlight and summarize the wide range of HMD developments over the past decades, it may be useful to briefly describe those efforts that have progressed all the way from initial R&D, through prototyping and production, and into fielding (even if limited). Some of these programs will be summarized in greater detail in the *Current and Future HMD Programs* section of this chapter.

One of the earliest (1970s) sighting HMD systems to be fielded was the electro-mechanical linkage head-tracked sight used to direct the fire of the gimbaled gun in the U.S. Army's AH-1G Huey Cobra attack helicopter (Braybrook,1998). The pilot aimed the gun by superimposing a helmet-mounted reticle over the target.

Not too long after the Cobra head tracker system (1973-1979), the Navy introduced an electro-optical head-tracking system into its later Phantom models F-4J and F-4N fixed-wing jet aircraft, coupled with the radar and AIM-9H Sidewinder missiles (Klass, 1972). The Visual Target Acquisition System (VTAS), shown in Figure 3-8, consisted of photo diodes on either side of a "halo assembly" that mounted on the standard fixed-wing flight helmet. Sensor surveying units on either side of the cockpit scanned the helmet in the "head motion box." The pilot used a visor-projected reticle and cueing discretes to interface with the fire-control radar and missiles for daytime, off-boresight, air-to-air targeting.

As was the case with the Cobra application, these head trackers yielded a significant reduction in the time required to bring weapons to bear on target. VTAS was discontinued in the 1970's (Dornheim, 1995) due to its technological limitations.

The first complete VCS system to see operational use was the introduction in the early 1980s of the IHADSS by the U.S. Army in the AH-64 Apache attack helicopter (Figure 3-9). The head tracking technology in the IHADSS was the electro-optical technology similar to the Navy VTAS. However, the HMD technology was much more capable and provided higher resolution dynamic video imagery by using a miniature 1-inch CRT with relay optics.

The monocular IHADSS serves as the crew interface for both the pilot and copilot/gunner. The pilot's IHADSS is interfaced with a 30° x 40°-FOV thermal sensor (mounted on the nose of the aircraft) to form a head coupled, one-to-one magnification pilotage system. The copilot's IHADSS is interfaced with a switchable-FOV thermal targeting sensor to form an effective off-boresight interface with the head-slaved gun and missiles. In both cases, the appropriate flight-control or fire-control symbology is mixed electronically with the thermal imagery. The systems have been used effectively for both day and night missions for almost three decades (Rash, 2008).

Recently, in the fixed-wing community, the U.S. Air Force and U.S. Navy have introduced the Joint Helmet-Mounted Cueing System (JHMCS) into the F-15, F-16 and F-18 aircraft. The JHMCS utilizes magnetic head tracker technology and provides a monocular, visor-projected display of stroke-written dynamic symbology from a ½-inch miniature CRT and relay optics (Figure 3-10). The JHMCS provides a daytime air-to-air and air-to-ground off-boresight targeting capability, especially valuable when used with high off-boresight missile seeker technology.

Figure 3-8. Visual Target Acquisition system (VTAS) HMD.

Figure 3-9. Integrated Helmet and Display Sight System (IHADSS).

Figure 3-10. Joint Helmet-Mounted Cueing System (Vision Systems International).

The U.S. military Services began working on a class of VCS called multi-mode HMDs in the mid 1980's. A multi-mode HMD, in a single integrated system, functionally provides an image-intensified view of the wearer's environment (similar to NVGs), as well as a day/night display of spatially-referenced imagery (e.g., low-light level TV, forward-looking infrared [FLIR]) and symbology like a traditional VCS. This is illustrated in the example shown in Figure 3-11. The U.S. Navy first implemented a developmental model based on IHADSS, and numerous R&D efforts including U.S. Army Comanche HIDSS program and U.S. Navy Advanced Helmet Vision System program, which pursued both discrete optics and visor-projected versions of this class of system. These types of head-coupled systems not only functionally perform the night NVG and day/night HMD mission, but they also provide "sensor fusion" capability by simultaneously presenting correlated, spatially-referenced information to the user in the visible and near/far infrared regions of the electromagnetic spectrum. Recent developmental multi-mode HMDs, e.g., the Comanche HMD and Advanced Helmet Vision System programs, current HMD efforts for the Joint Strike Fighter (JSF) for the U.S. Navy and U.S. Air Force, and the AH-1 upgrades for the U.S. Marine Corps, are binocular/biocular, helmet-mounted vision systems.

Outside the United States, the first "modern" helmet-mounted sight (HMS) was the optically-sensed Russian design, developed to support the Vympel R-73/AA-11 Archer high off-boresight seeker, air-to-air missile, carried by the MiG-29 Fulcrum and the Su-27 Flanker, and built to attach to the ZSh-5 series Russian helmet (Beal and Sweetman, 1997). Even though this HMS (Arsenal's Zh-3YM-1) was relatively rudimentary, lacking missile-cueing symbols and using only a flip-down monocle with a light-emitting-diode (LED) reticle for aiming, the combination of the HMS and R-73 missile provided the Soviets with a greatly improved close combat capability (Merryman, 1994). The Arsenal Design Bureau (Kiev, Ukraine) subsequently improved on this first HMS with newer versions, like the Sura and Taurus. The combination MiG-29/ AA-11 were sold to the air forces in India, Iraq, North Korea, Libya, Syria, Iran, Yugoslavia and potentially Cuba (Lucas, 1994).

During the Cold War the Russians developed and deployed force-multiplier HMD and HMS systems that gave them an edge on air superiority and then sold these systems to (then) unfriendly nations. The combination of an

HMD-guided, 4th generation (GEN-4) missile and even inferior aircraft reduced to zero the technology advantage enjoyed by U.S. fighter aircraft. This caused a surge in HMD development programs in the Western countries.

The Israeli Display and Sight Helmet (DASH) 3/ Python 4 combination (1990s) had an equally important impact on HMD development. The Python-4 was a missile system that had limited "fire-and-forget" capability, as well as helmet-sight guidance. The DASH HMS system by Elbit Systems was developed for Israeli F-15s and F-16s and will be discussed in more detail in the *Current and Future HMD Programs* section later in this chapter, as it is considered to have played an important role in the development history of today's HMD.

Advantages of Helmet-Mounted Displays

There is little argument that displays and their ability to provide information are a distinct advantage in any operational setting. It would be unthinkable to offer an automobile design that failed to provide the driver with displays that provide real-time presentations of such operational parameters as speed and fuel status. While such information is not critical to the second-to-second operation of the automobile, drivers depend on being able to "look down" at the display console and obtain this information as needed.

However, there are operational settings where certain displayed information is critical on a second-to-second basis. For example, in fast-moving aircraft flying close to the ground, the operational environment changes so rapidly that even the brief time it takes a pilot to glance down at one or more displays to obtain aircraft flight status information may severely degrade his/her situation awareness. This short-coming of "head-down" displays gave rise to the development of head-up displays (HUDs) (Figure 3-12). HUDs employ fixed, transparent pieces of glass or plastic mounted inside the aircraft windscreen (e.g., combiners or beamsplitters). HUDs allow critical flight data to be accessed in a head-up, eyes-out scenario. This offers a tremendous advantage in applications where the time taken to view head-down displays can negatively impact safety and performance. The use of HUDs is not limited to aircraft. They have been employed in racecars, another application where outside operational conditions change so rapidly that a constant eyes-out requirement exists (Qt Auto News, 2006).

HUDs also are finding applications in less demanding vehicles. In an attempt to reduce accidents by preventing extended attention to head-down radio and CD-player knobs and buttons, a number of car manufacturers offer a windshield HUD. General Motors offers a HUD option on its Cadillac XLR/SRS models. The HUD presents a speedometer, turn signal indicators, audio system data, gear indication and cruise control settings (Dupont Corp, 2004).

But, as advantageous as HUDs are, they are fixed forward and are not as useful when the user is required to exercise constant head movement, e.g., constantly searching for enemy aircraft in a 360° environment. This factor played an important role in the motivation to mount the display on the head (or other head-mounted platform such as a helmet).

The potential benefits of HMDs have captivated the aircraft community for 40 years. The HMD concept can be extended and transferred to other areas where a wide field-of-regard is beneficial. While early HMD development was aviation driven, their utility beyond aviation has not been overlooked. Tank commanders can benefit by staying in touch with the "outside world" while remaining protected. Dismounted soldiers (classic infantry) can maintain constant situation awareness of the digital battlefield as well as expanded and enhanced sensory inputs via HMDs.

Nevertheless, the basic virtue of HMDs is to provide the ability to "look and shoot" at a target as fast as possible after target identification is completed. A dog fight usually lasts 30 to 60 seconds – the few seconds saved by eliminating aircraft pointing gives the pilot a vital advantage. Using the HMD, the pilot can quickly "tag" the enemy aircraft, launch a missile, and then turn to the next target and repeat the procedure. Sequential targeting enables a pilot to deal with multiple threats simultaneously, by eliminating the limitation posed by aircraft maneuverability.

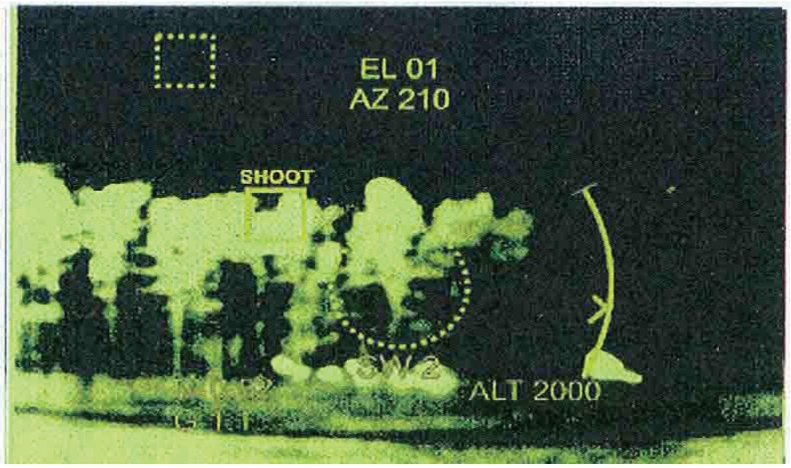

Figure 3-11. Example of multi-mode imagery with dynamic symbology.

Figure 3-12. Example of head-up display (HUD) in F/A-18C (National Aeronautics and Space Administration).

The dramatic threat coverage improvement provided by the wide field-of-regard of HMDs is shown in Figure 3-13. Comparisons are shown for a HUD, typical forward-looking radar, and off-boresight missile system.

The process of actively "tagging" targets is not limited to the individual platform: the pilot can identify a target and pass the information to an air surveillance and control platform (e.g., the Airborne Warning and Control System [AWACS] and Joint Surveillance Target Attack Radar System [JSTARS]), to other own sensors, or to another aircraft. Similarly, the opposite is useful as well - a detected threat by another platform or aircraft can be used to add cueing information to the HMD (Chapman and Clarkson, 1992).

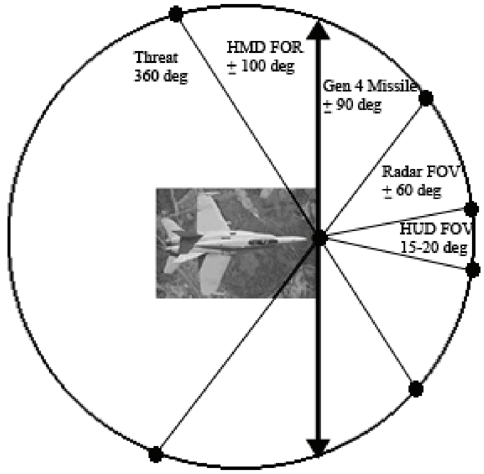

Figure 3-13. Depiction of expanded HMD/ HMS threat coverage.

For this reason, HMDs have increasingly been replacing and augmenting standard console-mounted head-down and traditional HUDs in advanced crew station designs. HMDs offer potentially greater direct access to critical visual information, while offering greater flexibility of head movement, less total system (but not user head-borne) weight, and greater flexibility in use of vehicular interior space, although at the cost of greater system complexity and possible expertise degradation in the case of system malfunctions.

More importantly, it is argued that HMDs provide users with increased situation awareness. Situation awareness encompasses the total information available, used to create an accurate picture of a battle theater, including spatial position and orientation of the aircraft, the surrounding areas, and any aircraft-relevant information. The pilot has to be aware of many different forms of information which is used to make judgments on how to respond to a given situation; any subtle level of perceptual cognizance to one's immediate environment can be vital for success in most situations (McCann and Foyle, 1995). The following operational definition of situation awareness has been proposed by a U.S. Air Force Staff Group: “A pilot’s (or aircrew’s) continuous perception of self and aircraft in relation to the dynamic of flights, threats, and mission, and the capability to forecast, then execute tasks based on the perception” (Geiselman, 1994).

In general situation awareness can be classified into Global (the "far domain") and Tactical (the "near domain"), covering close combat and navigational areas (Lucas, 1994). *Global situation awareness* refers to the range between 50 and 200 miles from the aircraft and related information is available from the main display on the instrument panel; whereas, *Tactical situation awareness* is the close range area within 50 miles, with information in the forward visual path. Each of these has associated temporal drivers as well, with faster reactions required the closer the relevant stimulus. This makes it physically impossible to see both domains simultaneously. As a result, pilots adopt a sequential acquisition scanning strategy by transitioning back and forth from the head-down instrument display to outside viewing, sampling information from first one domain, then the other. This recurrently interrupts the process of information acquisition and requires time-consuming actions, such as eye and head movements, eye accommodation, and becoming reacquainted with the alternating domains. Furthermore, as long as the pilot is looking at one domain, a sudden event (or sudden state change) in the other domain may be undetected.

By centralizing critical flight information within a user’s line-of-sight, overall performance is increased and operational safety is enhanced. HMDs offer users the advantage of monitoring critical information without having to repeatedly look down to scan instrument displays. Another proven benefit is that, with the ability to keep their eyes fixed to the outside world, users are more likely to detect important changes within the FOV (Harris and Muir, 2005: Manning and Rash, 2007). A specific example of the utility of this advantage is the greater probability in identifying runway incursions in military, civil and commercial aviation due to increased ability to maintain eyes out of the cockpit. Figure 3-14 depicts a typical HMD image. Note: This centralizing of critical flight information on front of the user's eye(s) should not be confused with the placement of the information (symbols) themselves, as early development of HMDs showed that symbology is most effective when placed around the periphery of the HMD imagery.

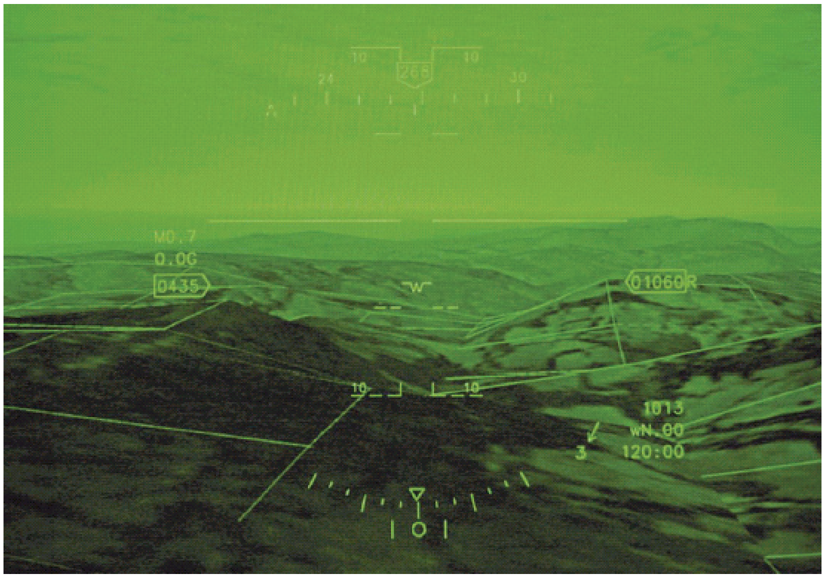

Figure 3-14. HMD Display (BAE Systems).

Limitations and Disadvantages of Helmet-Mounted Displays

Unfortunately, HMDs are not without their limitations and disadvantages. Some of the disadvantages are common to their predecessor, the HUD. First is the phenomenon of "attention capture" – or tunneling – which is the unwanted tendency for pilots to pay too much attention to the HUD and not enough attention to events in their field of vision outside the airplane (Foyle et al., 1993; McCann et al., 1993; McCann and Foyle, 1995). Attention capture with HUDs mounted just inside a windshield has been blamed for undetected runway incursions – one of the types of events that HUDs are to prevent. Numerous studies have attempted to understand attention capture and how it can be mitigated. Most disturbing is a developing consensus that HUDs (and hence HMDs) limit a pilot's ability to simultaneously process information derived from HUDs and from the real world (McCann et al., 1993).

Many HUD and HMD symbols are not "conformal" – that is, they are not overlaid in a one-to-one relationship to match shapes and features in the real world. Therefore, the symbols are perceived as different from the scene outside an aircraft's windows. This causes pilots to deliberately shift their attention to view either the symbols or the outside scene. The transition to conformal symbology may mitigate the attention capture problem (Wickens and Long, 1994). This conformity must be required for video imagery presented in HMDs. In other words, information is generated and presented based on conventions that users have to learn (train) to recognize: cognition processes as intuitive as they may be, are always slower than the instincts.

A second disadvantage is the possibility that HUD symbols or other imagery could obscure critical objects in the outside scene (Foyle et al., 1993). This problem can be reduced by keeping the number of symbols presented to a minimum and within the recommended size. Reducing the clutter caused by too many symbols also can decrease the potential for attention capture.

In addition to these general HUD-related disadvantages, other concerns are unique to HMD, as well as unique to the concept of mounting the display to the head. The first of these is user acceptability, which is important when any new technology is introduced; without user acceptance, the technology will not be used. The primary factors affecting acceptance are the head-supported weight, center-of-mass offset, required modification in head movement, display image quality/legibility, and display jitter and lag.

Most non-military pilots are not accustomed to wearing more than a headset on their heads. Current civil and commercial aviation headsets are generally lightweight, typically 12 to 18 ounces (340 to 510 grams) (Rash, 2006a). HMDs can increase head-supported weight by at least 16 ounces (454 grams). Military pilots wear helmet-based HMDs that weigh in excess of 4 pounds (lbs) (1.8 kilograms [kg]).

Because the HMD's display optics must be placed around the helmet with at least the combining element/visor in front of the eye, the HMD's additional weight is likely to be above and forward of the human head's natural center of mass - a factor that, as a flight progresses, may result in muscle fatigue.

For HMDs to present sensor and synthetic imagery that represent what a user is seeing, the HMD must incorporate head-tracking. The need for head-tracking increases the cost and the complexity of HMDs.

The head-tracking process of determining the user's head position, relaying this position to the sensor, the sensor's movement to the correct line-of-sight, the sensor's acquisition of the scene, and transmitting and presenting the final imagery on the HMD takes time (Rash, 2000). This time is called system latency. Latency times are typically hundreds of milliseconds (ms). The largest contributor is the "slew rate" of the sensor, or the time for the sensor to move to the line-of-sight defined by the new head position. Studies have shown that total system-latency times approaching one-third of a second or longer (~300 ms) are unacceptable from a performance standpoint. Many in the VCS community today are trying to achieve a total system latency time of less than one display frame time (typically 33 ms).

These latency times have been blamed for motion sickness. The onset and severity of motion sickness symptoms are difficult to predict, and such occurrences in commercial aviation would be unacceptable. Studies by the U.S. National Aeronautics and Space Administration (NASA) have documented the need for improvement in image alignment, accuracy and boresighting of HMDs to help mitigate this problem (Bailey et al., 2007).

Helmet-Mounted Display Applications

There is general agreement that HMDs have great potential applications; why, then, have only a few systems (mostly military) been fielded? Many factors contribute to this situation: cost, lagging technology, less than optimal ergonomics design (Keller and Colucci, 1998), unfinished search for that "application" that will excite users, unawareness of the potential benefits, and simply the "visceral dislike" (Hopper, 2000) of wearing a monitor on ones head. Four decades into the HMD exploration, the "killer application" that will propel the technology has not yet been identified.

Ivan Sutherland (1965) proposed the "Ultimate Display", more than 40 years ago (Figure 3-15). While at the Department of Computer Science, University of Utah, Sutherland imagined a display in which all-powerful computers would generate graphics of objects that would behave exactly (in all sensory modes) as their real-world counterparts. Implied in his concept were certain characteristics and expectations: a) the need for a complete sensory response: sight, sound, smell, feeling (haptic), and kinetic feedback to create the new reality and b) the use of HMDs will serve as a step toward an intuitive interface between human and machine, a natural way to add 3-D to an otherwise flat computer imagery. This display is still far into the future, but the anticipated technologies have come to fruition as we have moved into the 21st century. Others still are found only in science fiction. Nonetheless, Sutherland's HMD concept opened the way to computer-generated 3-D stroke images coupled with head trackers – the same basic principles applied today.

Figure 3-15. Ivan Sutherland's HMD (late 1960’s) (Department of Computer Science, University of Utah).

The military has led in the applications of HMDs, and there is a growing interest in industrial and consumer applications. Some current and future potential applications are listed below. It must be noted that there are no rigid boundaries between these applications, as some applications have multiple usage across these boundaries. The use of HMDs in simulation and training has been adopted by both military and industrial users, and has served as a precursor to consumer gaming.

Military applications include:

- Navigation and situation awareness
- Targeting
- Night vision systems
- Visual enhancement
- Security monitoring
- Simulation and training
- Maintenance and inspection
- Remotely-piloted vehicle interface

Commercial applications include:

- Computer-aided design/ Computer-aided engineering (CAD/CAE)
- Surgical aid - microsurgery, endoscopic surgery
- Emergency medical telepresence
- Security monitoring
- Maintenance, Repair and Overhaul (MRO)

Consumer applications include:

- Gaming
- Mobile Internet access
- Private DVD viewing
- Fire-fighting

The following sections briefly describe and discuss some of the more important and interesting applications within the three areas: military, commercial and consumer.

Military applications

Military applications are the focus of this book – the merits of HMDs for both fixed- and rotary-wing aircraft are beyond questioning, and HMDs already have become an integral part of the next-generation cockpits. Much of this success is due to the use of head/helmet-tracking to produce visually-coupled HMD systems.

Use of visually-coupled systems (VCS) for pilotage, navigation and/or situation awareness

VCS technologies have been used for a tremendous variety of mission applications over the years. As previously noted for early applications of helmet-mounted sights, head-position sensing was used for a variety of line-of-sight designation and targeting in conjunction with onboard weapons and sensors. Some of the earliest investigations of HMD technologies were designed as a way to investigate a wider FOV display in cockpits or crew stations of various air, ground, and maritime vehicles.

Over the years, the military has interfaced helmet-mounted sights and HMDs to a wide variety of vehicle systems and weapons. They have been linked with radars, electro-optical/TV missile systems, reconnaissance sensors, long-range target identification sensors, pilotage sensors, head-slaved guns (both air-to-ground and surface-to-air), and angle-rate bombing sensors. They have been interfaced with distributed aperture sensor systems for a total coverage "windowless cockpit" synthetic vision system capability for both aircraft and ground vehicles. They have been used to present spatially-referenced "highway-in-the-sky" type flight control information for both fixed-wing ejection seat aircraft and rotary-wing operations and for shipboard landings, and to present "predictor" fire control dynamic symbology such as "hotline gun sight." These are fairly typical VCS applications.

There have also been some "non-traditional" VCS applications attempted by the military over the years. One example is the use of a head tracker and HMD as an effective operator interface with a remotely piloted vehicle. By using VCS, the "illusion" can be created for the operator that they are "out there onboard the vehicle." The military has successfully interfaced VCS with airborne, ground-based, and undersea unmanned vehicles for a wide variety of missions including reconnaissance, targeting, bomb disposal, undersea operations and other teleoperator applications.

Virtual cockpit

The "Virtual Cockpit" is a second application that has moved forward in the military with the main goal of providing a "software reconfigurable cockpit." In the late 1990s the U.S. Army's Program Manager-Aircrew Integrated Systems (PM-ACIS), Huntsville, Alabama, initiated the Virtual Cockpit Optimization Program (VCOP) to integrate advanced technologies into a single system. VCOP technologies included a Retinal Scanning Display (RSD); fully integrated 3-D cockpit audio technologies with speech recognition and synthesis; an Integrated Caution, Warning and Advisory Annunciator (ICWAA); and an Electronic Data Manager (EDM); all integrated and managed by the Rotorcraft Pilot's Associate (RPA) Software. These technologies were intended to enhance situation and threat awareness, while at the same time providing a cost-effective technique to modernize legacy aircraft. In its simplest configuration, VCOP goals were to:

- Provide efficient access to critical information with minimized "head-down" time;
- Formulate "standardized" dashboard panel requirements; and

- Establish an environment for rapid avionics prototyping, integration, test and evaluation of multiple aircraft configurations.

A similar program was initiated in Japan, in the early 2000's, by a team coordinated by Kawasaki Heavy Industry and Yokogawa Electric Corporation (Bayer, 2007). Similar to U.S. Army's VCOP, this program's goals were to:

- Minimize cockpit cost and weight;
- Develop reconfigurable configuration between manned- and unmanned combat aircraft; and
- Increase pilot's situation awareness.

Virtual Reality (VR)

We have seen that HMDs can be designed to be see-through (transparent), in which case the sensor- or computer-generated (synthetic) imagery is overlaid on the actual physical world outside, or nonsee-through (occluded), where the user only sees sensor- or computer-generated imagery. In the former case, the HMD is said to create an Augmented Reality (AR), i.e., adding information to the world around the user. In the latter case, specifically when the HMD presents only computer-generated imagery, the situation is referred to as Virtual Reality (VR); the real world is completely obscured, with computer-generated imagery being the only visual information the user receives.

AR and VR are related, and it is valid to consider the two concepts together in terms of a continuum linking purely virtual environments (VEs) to purely real environments. The VR environment is one in which the participant/observer is totally immersed in a completely synthetic world, which may or may not obey the properties of a real-world environment. Indeed, it is possible in VR to exceed the bounds of physical reality by creating a world in which the physical laws governing gravity, time and material properties no longer hold. In contrast, the strictly real-world environment clearly is constrained by the laws of physics.

Rather than regarding the two concepts simply as antitheses, however, it is more convenient to view them as lying at opposite ends of a continuum, which is referred to as the *Reality-Virtuality (RV) continuum*. This concept is illustrated in Figure 3-16 (Milgram, 1994).

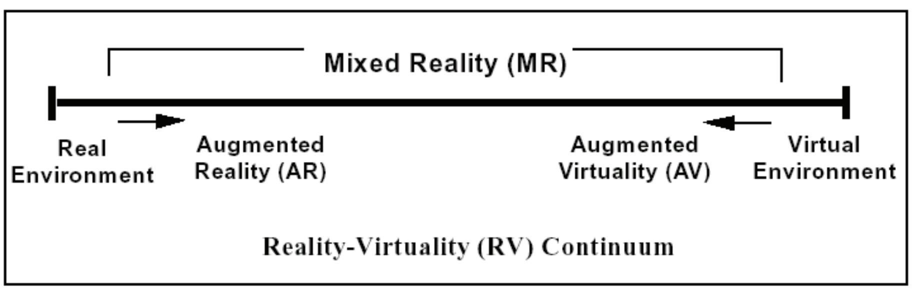

Figure 3-16. Reality-Virtuality Continuum (Milgram, 1994).

The *Real Environment* (RE) (extreme left) consists solely of real objects and is observed when viewing a real-world scene either directly, or through a 100% transparent window. The *Virtual Environment* (VE) (extreme right), defines environments consisting solely of virtual objects, e.g., computer graphic simulations; RE is completely suppressed here. The Mixed Reality (MR) environment is one where real and virtual world objects coexist and are presented together. The HMD is the mechanism that brings the MR to existence. Its level of transparency to the real world positions the "instantaneous" reality on the MR continuum line, depending on whether the HMD is a "see-through" or "opaque" configuration.

Whether the environment is Augmented Reality or Augmented Virtuality, depends of whether the presented environment is primarily real, with added computer generated graphics, or is primarily virtual, but augmented through the use of real (i.e. un-modeled) imaging data (Drascic and Milgram, 1996).

In summary, AR systems bring the computer to the user's real environment, whereas VR systems bring the world into the user's simulated computer-generated environment. This paradigm for user interaction and information visualization constitutes the core of a very promising new technology for many applications. However, real applications impose strong demands on AR technology that cannot yet be completely met at the current level of technology.

Simulation, training and mission rehearsal

Next to aviation applications, simulation, training and mission rehearsal are probably the best known HMD-based VR applications for military purposes (Haar, 2005). The military and NASA have had substantial R&D efforts aimed at using VCS as an alternative to large domed simulators. By doing this, resolution and graphics power can be concentrated into the instantaneous FOV of the subject, providing a higher performance system. Special techniques such as foveal/peripheral image generation and eye position sensing (eye tracking) have enhanced the operator interface in some of these systems. By creating a virtual world and a virtual cockpit, changes in crew station design can be investigated in this “virtual world” before real-world hardware is redesigned and modified.

Combat simulators are well established and offer an excellent fit with HMD-based applications. In conjunction with powerful computer systems, they can simulate and integrate entire environments within a single display. The fundamental difference between simulation and training is that the former often is used as a tool for development, evaluation and validation of new designs or to visualize results of complex computations that result in large 3-D graphics (Casey, 1991). Training is presenting the same sets of video scenarios with already known solutions to multiple users and interactively evaluates their response time and degree of accuracy of the solutions offered.

Simulation techniques and applications have greatly expanded with the apparently never-ending increase in computer processing power - from flight training into war simulation with a complete air fleet. Display performance requirements for such application are among the most demanding of all. For best results, simulation fidelity must match physical reality that will be encountered in the field. HMD-based simulation arguably is the best way to perform realistic simulation.

Flight training

The Aviation Combined Arms Tactical Trainer – Aviation Reconfigurable Manned Simulator (AVCATT-A) (Figure 3-17) is an aviation training simulator for both active U.S. Army and National Guard units. It is a dynamic reconfigurable system used for combined arms collective training and mission rehearsal through networked simulators in a simulated battlefield environment. AVCATT-A provides five functional cockpits: the OH-58D Kiowa Warrior, the AH-64A Apache, the AH-64D Apache Longbow, the CH-47D Chinook, and the UH-60A/L Blackhawk helicopters.

The AVCATT-A is purely a helicopter *combat* trainer and not a *flight* trainer. There is no extent of motion, and it does not give the trainees a sense of flying the helicopter. Only instruments that are specific for combat operations are usable. Its greatest asset is that it provides a unique capability to allow units to train as units and not as individual aircrews. The AVCATT-A provides the capability to conduct realistic, high intensity, task loaded collective and combined arms training exercises and mission rehearsals of current Army attack, reconnaissance, cargo, and utility aircraft.

The physical layout of an AVCATT-A suite consists of two trailers connected by a platform. One trailer includes three reconfigurable manned modules and a 20-person After-Action Review facility. The second trailer includes three reconfigurable manned modules, a Battlemaster Control room, and a maintenance room.

AVCATT-A provides a total capability of six manned module cockpits per suite, networked together to help train an aviation company or air cavalry troop. Each manned module is reconfigurable to current Army attack, reconnaissance, cargo, and utility aircraft. AVCATT-A has the capability to be linked via local area network (LAN) and/or wide area network (WAN) with other AVCATT-A suites, and other combined arms tactical trainers such as the Close Combat Tactical Trainer (CCTT). This provides the capability to conduct collective training from team through combined arms levels (Simons et al., 2002). The AVCATT-A visual system (Figure 3-18) creates the Out-the-Window (OTW) and sensor imagery view.

Figure 3-17. Pilot in the AVCATT-A System.

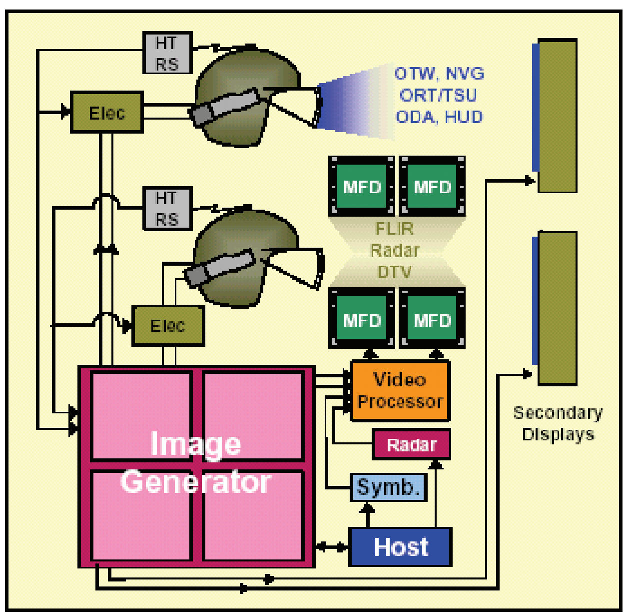

Figure 3-18. AVCATT-A visual system.

The major components of the AVCATT-A visual system are the Image Generator (IG), two HMDs, two Multifunction Displays (MFDs), and two secondary (backup) displays. The IG provides the imagery for the pilot and copilot, as well as two sensor channels. The HMD (a Rockwell Collins Model SimEye™ XL100A) is a high-resolution, full color head-mounted display that traces its origins to the Wide-Eye™ HMD designed for the U.S. Army's Light Helicopter Experimental (LHX) program (1980s), which was the predecessor to U.S. Army's Comanche program of the 1990s.

Driver trainer with mission rehearsal

Some U.S. Army vehicles now have embedded training, such as the simulator built into a Bradley Fighting Vehicle, based on the BAE Systems (U.K.) Bradley A3 Embedded Tactical Training Initiative (BETTI). This system enables soldiers to train with realistic-looking simulated terrain while they are sitting in their vehicles in the belly of a C-130 cargo plane, in route to the area of operation. When the aircraft's ramp drops to the runway, Warfighters drive directly from the virtual world into the real one. However, for Mission Rehearsal Exercises (MREs) to work, the simulations must have enough fidelity to earn troops' confidence that they will be able to draw on their simulated lessons in the heat of battle. The key challenge is to achieve a "real immersion," to faithfully replicate scenarios, and to represent the physical world in the display environment in a believable manner.

Commercial applications

The basic concept of an HMD as a head-up mode for information presentation has been of interest to various sectors of the commercial and industrial communities. However, in spite of less demanding environments, non-military applications must face a number of unique hurdles that include:

- What are the benefits an HMD-based system brings to the application (e.g., easy access to information, privacy, stereo imagery, wide field of regard)?
- What are the logistical, human factors, and ethical issues associated with the choice of an HMD over that of current direct view displays, e.g., privacy, transportability, storability?
- Is the technology mature enough to perform acceptably in the application?
- Do the cost and added inconvenience justify an HMD approach?

In general, once the cost/benefits issues have been evaluated and found acceptable, one of the remaining chief barriers to commercial applications of HMDs is user acceptance. Most commercial and industrial workers (construction workers being an exception) are not used to having to wear any type of head-gear. Head-supported weight, center-of-mass offsets, pressure points, sweating, and overall discomfort are common complaints of such devices, and such issues have certainly had a negative impact on user acceptance and, hence, the implementation of HMDs. Developers, aware of these problems, have pursued such solutions as designs no more cumbersome than simple eyeglasses. However, eye-wear HMDs come with their own set of limitations, with a narrow FOV (usually less than 20°) being probably the most critical.

Nonetheless, a number of commercial applications do exist. As such issues as head-supported weight and overall discomfort are addressed by low-weight designs, the advantages of HMDs will eventually increase this number. Potential application areas will be those where users can benefit from visualized information otherwise not available or difficult to obtain due to certain task constraints.

In the following sections, a few commercial applications are briefly described. While as in military applications, the aviation-related ones are predominate, many medical applications presenting diagnostic and surgical imagery are emerging, as HMDs offer an alternative method of presentation of this imagery.

Instrument landing

The National Research Council's (NRC's) (Canada) Cockpit Technologies Program has flight tested a stereoscopic 3-D display format to determine the feasibility of using HMD-presented pictorial and stereoscopic cues during helicopter Instrument Approach Procedures (IAP) (Jennings, 1997). Pilots were able to complete approaches to safe landings and reported that the pictorial format improved their situation awareness during the approaches. While lacking stereo cues, the pictorial display contained several strong monocular depth cues such as occlusion, linear perspective, and visual field-flow (motion). This type of system would be extremely useful during Instrument Meteorological Conditions (IMC), when the outside world is obscured, and pilots can no longer use external visual cues for maintaining control of the aircraft.

Training

The potential of HMD-based VEs for training simulation has been recognized right from the emergence of this technology. The Federal Aviation Administration (FAA) is pursuing research focused on the aircraft inspection processes. Existing training for inspectors in the aircraft maintenance environment tends to be mostly on-the-job training;, however, feedback to the trainee, may be infrequent, unmethodical, and/or delayed. One of the most viable approaches in the aircraft maintenance environment, given its many constraints and requirements, is computer-based training which is efficient, facilitates standardization and supports distance learning.

A recent example is the Automated System of Self Instruction for Specialized Training (ASSIST), featuring a personal computer (PC)-based aircraft inspection simulator. Despite the advantages, the simulator is limited by its lack of realism, as it uses 2-D sectional images of airframe structures. More importantly, the inspectors are not immersed in the environment, and, hence, they do not get the same look and feel as when conducting an actual inspection. To address these limitations, a VR-based inspection simulator using an HMD has been developed (Duchowski, 2000).

Analysis of performance data with this environment (Vora, 2002) revealed a significantly greater number of defects identified within a significantly shorter visual search time in the VE in comparison with the ASSIST environment. When these results were coupled with subjects' perception of the two systems, the VE system was preferred to the ASSIST as an aircraft inspection training tool by a ratio of almost 3:1, proving the potential effectiveness of an HMD-presented VE in improving both speed and accuracy of visual search.

Surgical planning and diagnostic tasks

A see-through HMD has been used by surgeons to view preoperatively scanned images (e.g., ultrasound, x-ray, Magnetic Resonance Imaging [MRI]), as if looking through the patient at the internal organs (Bajura, 1992). Key to the implementation, of course, is accurate color rendition and accurate registration of the 3-D graphics to the real world.

Surgery

Great advances have been made in reducing the invasiveness of surgical procedures. Many surgeries today are performed through either natural body openings or through small incisions, with the surgeon viewing the surgical field indirectly via a remotely operated camera which has been inserted into the operative field. Today, surgeons routinely remove appendixes, gallbladders, spleens and other organs and tissues by laparoscopy. The most qualified are now macerating and removing kidneys, pancreases, colons, adrenal glands and other more complicated organs, or repairing them without open surgery. In the vast majority of cases, the surgeon views the imagery on monitors located at some distance away. HMDs can allow the surgeon increased eye-hand coordination, situation awareness and flexibility as compared to viewing remotely positioned monitors, especially when coupled to teleoperated and robotically assistive instruments. In demonstrations of this application, computer generated graphics (i.e., AR) have been integrated into the HMD imagery (Ackerman, 2002).

Molecular studies

At University of North Carolina (UNC) at Chapel Hill, three major fields of research: interactive molecular studies, medical imaging and virtual building exploration are making use of the advantages of HMDs (Chung, 1989).

Macromolecules have complex 3-D structures and understanding them is often the key to explaining material chemical properties. Researchers at UNC envision a system where chemists use an HMD to view a room-sized, 3-D virtual molecule to study its external structure by “walking” around its exterior, to “enter” the molecule to examine the internal connections, and perhaps (in the future) to cause the molecule to respond to changes in ambient conditions.

Virtual Reality Dynamic Anatomy (VRDA)

A cooperative effort of Optical Diagnostics and Application Laboratory (ODALab) (Orlando, FL), 3-D Visualization (3DVIS) Laboratory (Tucson, AZ), and Media Interface and Network Design (MIND) Laboratory (Tucson, AZ) has investigated a couple of interesting WR applications. One of these is the VRDA concept, which is a visualization tool for teaching complex anatomical joint motions (Rolland, 2002). The VRDA allows a trainee to manipulate an anatomical joint and visualize the virtual model of the inner anatomy superimposed on the body using marker based techniques. Coupled with tactile phantoms, this can become a very immersive experience.

Airway management visualization and training

To open blocked airways, it is sometimes necessary to perform an endotracheal intubation (ETI) which consists of inserting a tube through the mouth into the trachea and then sealing the trachea so that all air passes through the tube. In an effort to improve training and keep them current, the U.S. Army Simulation, Training and Instrumentation Command (STRICOM) (Orlando, FL), and Medical Education Technologies, Inc. (METI) (Sarasota, FL), who provided the human patient simulator, teamed with ODALab to develop the Airway Management Visualization and Training for paramedics (Davis, 2002). This is an HMD-based AR system that allows paramedics to practice their skills and provides real-time feedback of their performance and suggests improvements/corrections.

Telepresence

Conventional telepresence usually is implemented through a pan and tilt camera system controlled by a joystick. This requires significant operator training and can be expected to lead to longer task execution. This is due to the constant requirement for the operator to adapt to the frame of reference from the camera. Nevertheless, studies have shown that telepresence, when accompanied by stereoscopic displays, brings definite benefits to the person operating remote equipment (Reinhart, 1991). Some applications include telerobotic fields, e.g., remote mining, nuclear sites inspection, space exploration, mine clearing equipment, instances where it is impractical for the human operator to be at the immediate location, whether for safety or other reasons.

A more advanced telepresence, currently in development, proof-of-concept stage is anthropometric telepresence (Primeau, 2000). Anthropometric telepresence is the next best thing to actually “being there,” with the added benefit of safe operation away from areas deemed too hazardous to have an operator on site. It is based on a camera system that is slaved in real-time to the operator’s line-of-sight. The information relayed back is presented in a natural way, which makes most training unnecessary; the operator is fully immersed in the remote site. Applications exist in space, military (piloting unmanned air/land/sea vehicles), law enforcement, industry (mining, oil exploration) and many other situations where hazardous situations exist or may develop without warning (nuclear, biological, chemical).

Consumer applications

Burdened with the same problems associated with commercial applications (e.g., discomfort, lack of acceptance of head-supported weight), it is not surprising that consumer applications have lagged even further behind. It is one thing to be paid to wear an uncomfortable device; but, doing so and having to pay for it is something else again. An exception to this argument is full-immersion computer games. Besides the VR aspects of state-of-the-art games, wearing a near-true-to-life HMD while flying an F-18 Hornet adds to the realism and the thrill. The potential for gaming is absolutely limitless. In general, the 3-D interactive games mimic military flight missions, space war games and otherwise unobtainable adventures.

Gaming

Personal gaming applications using head-worn displays are extensive. At annual gaming industry expositions, sophisticated full-immersion games, virtually all requiring some type of HMD, are the center of attention. Figure 3-19 depicts one of the latest entries in the fast-moving industry. It is the Trimersion HMD manufactured by 3001 AD,[5] touted as the "next level of realism by offering greater immersion inside the game via an HMD [acting as] a realistic and natural interface" (Gizmag, 2006).

The design uses built-in headphones and a headband system. The headband is described as a mask that surrounds the display optics. The manufacturer contrasts this design to others that employ either visors that allow external light to come into the line-of-sight of the player or eyecups that are uncomfortable. The Trimersion HMD mask curves around the player's cheekbones using soft rubber, providing a complete lightless enclosure.

Figure 3-19. 3001 AD's Trimersion gaming HMD.

[5]3001 AD, 430 South Congress Ave, Delray Beach, FL 33445

Current and Future Helmet-Mounted Display Programs

In this section, brief synopses of the more significant HMD programs will be presented. While most of these will be programs that achieved at least limited fielding, some are still in their research and development phase, and others were never fielded due to a variety of reasons but still represent significant advances in HMD design. The majority of these programs is military-related and represents worldwide efforts. However, a few commercial systems also are presented.

While most military programs were for rotary- and fixed-wing aircraft platforms, more recent programs have developed HMDs for use by both vehicular-mounted and dismounted Warfighters. Since training applications have increased, simulation HMD programs are also included. In a few cases, an HMD system may have applications on more than one platform.

The salient programs are presented first for fixed-wing platforms, then for rotary-wing platforms, and finally for the mounted-vehicle, dismounted and simulation platforms.

Military HMD programs: Fixed-wing platforms

A main HMD application that drove early development is target cueing. Since the mounting of machine guns on airplanes in World War I marked the official beginning of the evolution of pilot-centered weapons, pilots invariably had cued on the targets by pointing the nose of the aircraft in the direction of the target.[6] Introduction of the HUD marked the first step toward allowing pilots to cue their weapons with an out-of-the-cockpit aiming device. A giant leap forward in terms of pilot-to-aircraft interface, the HUD displayed not only accurate weapons-aiming symbols, but also relevant flight data such as airspeed, altitude, and heading. For the first time, pilots could view such information without looking back inside the cockpit.

The dynamics of airborne combat require pilots to outmaneuver each other. Air Forces around the world have run a technological race aimed at gaining superiority through increased propulsion and maneuverability of fighter aircraft that continued with second and third generation heat-seeking missiles. Although visually-coupled systems (VCS), the concept of linking helmet sighting systems with radars and missiles, as an operational capability dates back to the early 1970s, advances in both helmet vision systems and high off-boresight missile seeker technology of the current day brings a much more significant tactical capability to the Services today. Capable Air Intercept radars had several dogfighting modes that were designed to rapidly acquire and track a target. When the first fourth generation missiles appeared, e.g., the Soviet Vympel R-73 (AA-11 Archer) and the Israeli Rafael Python 4 (Beal and Sweetman, 1994), it was clearly apparent that with very large off-boresight angles, typically of the order of 90 degrees of arc, the old flight dynamics would no longer be adequate. Subjected to high-G forces, pilots risked loss of consciousness and extended incapacitation. Performance limitation moved beyond hardware to the human operator.

The arrival of the HMD as a cueing tool changed, and is continuing to change, this scenario. Superior aircraft speed and maneuverability agility are no longer essential factors to a successful engagement. The use of HMDs allows slaved air-to-air missiles, capable of more than 50Gs, to execute the high-G turn instead of the pilot; the HMD is a true force multiplier. Less proficient pilots flying inferior aircraft armed with a GEN-4 missile enjoy a distinct advantage because of the HMD. Essentially, HMDs are “must have” equipment on GEN-4 fighter aircraft, since high off-boresight weapons and visual cueing outweigh any aircraft-performance advantage during a dogfight. Experts believe that HMD cueing systems significantly increase the win probability for the same aircraft armed with a GEN-4 high off-boresight missile

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[6] Exceptions are the use of gun-turrets in multi-engine aircraft during WWII and side gunners in modern gunships and helicopters.

Cueing HMDs make it possible to synthesize the target information by using an HMD with a cockpit computer and onboard advanced weapons' capabilities. Position sensors on the pilot's helmet track the instantaneous pilot's line-of-sight as it follows the target. The sensors relay critical information to the computer, which in turn, communicates the location of the target to the missile system. When the weapons lock onto the target, the pilot receives both audio and video signals, and then pulls the trigger located on the control stick to fire the missile. The advantage of the few extra seconds gained by getting the missile launch first, could well make the difference between life and death.

The first high-off-boresight VCS test in the U.S. military took place in early 1994, at Tyndall Air Force Base, FL (Hughes, 1994). It was a conclusive demonstration of how a Honeywell HMD, a Raytheon missile, and a Lockheed F-16 could perform seamlessly as an integrated system and achieved 72° of off-boresight deflection with a 30G acceleration.

This scenario represents a total paradigm shift in the way air-to-air fighter combat is fought and brings back the advantage of independently swiveling gun turrets of older multi-engine aircraft. The sighting reference for cueing a weapon is no longer the nose of the aircraft but rather the pilot's HMD. As long as the target is within range and the pilot can view the target via the HMD, the relative position of the aircraft to the enemy is not critical. Tactical implications are profound and serve as the major driver for many if not all of the following HMD programs directed at fixed-wing platforms.

Table 3-1 presents a partial summary of the more notable experimental, prototype, fielded and future HMD fixed-wing programs. It followed by summaries of select HMD programs. Many of these HMDs are depicted in Figure 3-20. Many of the programs involved a number of contracts with various commercial HMD developers playing differing roles. Many of the programs also were multi-national in scope. The country of development listed in Table 3-1 and ensuing program descriptions generally is based on the initial developmental phase.

Display and Sight Helmet (DASH) series (Israel)

Elbit Systems Ltd. (Israel) developed a series of HMDs known as the (DASH) in the 1ate 1970’s (beginning with DASH 1) and was installed on the Israel Air Force F-15s and F-16s. Both air-to-air and air-to-ground configurations have been deployed. DASH 2 had an improved design, but was never produced in volume.

DASH 3 (Figure 3-20) entered production during the early 1990s in conjunction with the Rafael Python GEN-4 air-to-air missile. DASH 3 is currently deployed on IDF F-15C/D, the F-16C/D, the F-15I, the F/A-18C aircraft and has been offered to export customers, as part of upgrade packages for F-5E/F and also for Russian aircraft. Dash 3 has been implemented in the Romanian Mig-21 (Lancer) platform upgrade. This HMD deserves careful examination as it has been the first of the new generation of Western HMDs to achieve operational service and it also provides part of the technology base for the Joint Helmet Mounted Cueing System (JHMCS).

The DASH 3 is an “embedded” HMD design, where the complete optical and position sensing coil package is built into a standard helmet form factor, in this instance either the U.S. Air Force standard HGU-55/P or the Israeli standard HGU-22/P. The helmet is customized to individual pilot head shapes and sizes using either poured foam or Thermal Plastic Liners (TPL™). Once the helmet is fitted to the pilot, the optics is adjusted to position the HMD’s exit pupil to the pilot’s eye. DASH 3 accommodates eye glasses and standard oxygen masks. DASH 3 weighs 1.65 kg for the larger helmet size, and the helmet center of gravity is well balanced, meeting requirements.

A visor-projection optical configuration is used for this HMD. The projection on a spherical visor eliminates the risks and cost impact of an aspheric visor. Dash 3 provides a 20-degree FOV, with a 15-mm exist pupil for the optics. All symbology is calligraphic, produced by a programmable stroke generator.

The strength of the Dash 3 lies in its maturity and compact form factor, which is advantageous in a tight canopy (Koff, 1998). The system is operational in 5 countries, on 4 continents and onboard 5 different major platforms (F-15A/B/C/D; F-15I; F-16C/D; F-5E/F; MiG-21). Over 1000 Dash systems have been delivered to customers worldwide.

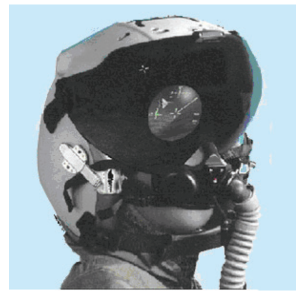

DASH 3

Agile Eye Plus (circa 1992)


Crusader


TopSight


Typhoon (Eurofighter) IDH


Joint Helmet Mounted Cueing System


HMDS


TopNight


Viper 3

Figure 3-20. Selected current and future fixed-wing HMD programs.

Agile Eye (United States)

Kaiser Electronics (now Rockwell Collins) has produced and tested a series of experimental systems since early 1980’s including several Agile Eye and Agile Eye Mark I to IV systems. Agile Eye Plus (circa 1992) is shown Figure 3-20. The Agile Eye Mark V, the Visually Coupled Acquisition Targeting System (VCATS), produced in 1995, is very important to the HMD technology development.

Agile Eye uses a small CRT in the back of the helmet to project imagery (symbology and targeting data) to the pilot’s eye via a set of relay optics and projection off the visor.

Table 3-1.
Summary of selected fixed-wing HMD programs

Time frame	Program	Country	Platform	Developer	Program status	Notes
1970s	Dash 1	Israel	Fixed-Wing F-15, F-16	Elbit Systems	Fielded	
Early to mid 1980s	Agile Eye	USA	Fixed-Wing Miscellaneous	Kaiser Electronics	Experimental	Mark 1 through 5 (VCATS)
Early 1990s	Dash 3	Israel	Fixed-Wing F-15, F-16	Elbit Systems	Fielded	
1990s	Viper 1-3	UK	Fixed-Wing Miscellaneous	GEC-Marconi Avionics Ltd (Delft Instruments)	Experimental	
Mid 1990s	Crusader	US/UK	Fixed- & Rotary-wing	Gentex/ BAE Systems/ Thales	Experimental	Technology demonstrator
Late 1990s	TopSight	France	Fixed-Wing Miscellaneous	Thales (Sextant Avionique)	Fielded	Day mission
Late 1990s	TopNight	France	Fixed-Wing Miscellaneous	Thales (Sextant Avionique)	Fielded	Night Mission
1999	JHMCS	USA	Fixed-Wing F-15, F-16, F-18	VSI	Fielded	
2008	Scorpion	USA	Fixed-Wing	Gentex	Operational Testing	
2008	Typhoon IHD	UK	Fixed-Wing Eurofighter	BAE Systems	Development	
2010	HMDS	USA	Fixed-Wing F-35	VSI	Development	

VCATS was extensively used as a design tool and test bed by the U.S. Air Force Research Laboratory at Wright Patterson Air Force Base, OH. The VCATS program was specifically designed to solve the technical and operational problems that historically had plagued HMDs, and it has paved the way to a successful JHMCS program. Some of the technology “building blocks” in VCATS were jointly supported by the Navy Science and Technology Base Program. Among the problems tackled on the VCATS was the introduction of a standardized helmet-vehicle interface (HVI) that uses interconnecting modules, which are easily replaced with minimal effort, down-time, or potential for error. Through the helmet and its connectors, the pilot becomes part of a closed-loop electronic system. The quick disconnect (QDC) connector also provides for emergency egress and allows “hot” disconnect without arcing.

VCATS also represents a prelude to a human-factors breakthrough. From the very beginning of air fight increased propulsion and maneuverability were the main two factors of improving the U.S. fighter pilot's advantage in the end game. The latest fighter aircraft speeds and agility levels place the pilot in the position of pulling dangerously high-force levels of up to 12Gs, maneuvers that can produce devastating results such as blackouts and extended incapacitation. With VCATS, however, the pilot continues to be limited to a safer 9Gs, while the missile may execute the high-G turn (in excess of 50Gs is now common) instead of the pilot, while in route to the target. VCATS introduced a human-centered system matching the pilot's physical and mental capabilities (the visual system, head-eye-hand coordination, decision-making abilities, and response time).

A summary of VCATS program findings and implementations is provided in Table 3-2.

Table 3-2.
VCATS findings and implementations.

Finding	Implementation
Eyeball critical sensor	No visor reflective patch
Keep system latency below the limit of being noticeable by pilot	Achieve 30-50 ms of latency; System integration
Interference suppression to smooth head bounce in high-G buffet	High update rate tracker; Accelerometers and digital filter algorithm for active noise cancellation
Keep static pointing errors < 5 mrad	Tracker algorithms; System integration
Use custom fit helmets to minimize slip under heavy G-load	Visor and mask custom trim

Viper Series (United Kingdom)

The U.K.-developed Viper HMD series included three models for fixed-wing operation. GEC-Marconi Avionics (now BAE Systems) developed the Viper 1 and 2 HMDs, which are CRT-based systems (Cameron and Steward, 1994). The Viper 1 became available in mid-1990s as a monocular, visor-projected HMD. It uses a 1-inch diameter miniature CRT display projected via an optical relay assembly, and it employs the standard aircrew spherical visor with the addition of a 70% transmission neutral density coating. This has the advantage of not coloring the ambient when viewed through. It is primarily a stroke-mode day-system, although it can also display raster images. The Viper 1 provides 20° circular FOV, with 15-mm exit pupil, and 70-mm eye relief. Excluding the oxygen mask, it weighs 3.8 lbs (1.7 kg). It was flight tested in the X-31 and also in the F-16 to demonstrate look and shoot capability.

The series continued with the Viper 2. It was BAE's first binocular visor-projected HMD and was flown in the JAST AV-8B (U.S. Version of Harrier), German Tornado, U.K. Tornado, and various F-16s. Designed in a binocular configuration, it used two of the same CRTs as Viper 1 and maintained the visor projection approach using a spherical visor with 70% transmission neutral density coating. The system was configurable to symbology only (stroke-mode), video display from an external source (raster mode) or hybrid video with symbology overlay (stroke-on-raster). It provided 40° FOV with full overlap, a 15-mm exit pupil, and a 70-mm eye relief. Excluding the oxygen mask it weighs 4.2 lbs (1.9 kg).

The Viper 3 (late 1990s) was designed to be a visor-projected NVG replacement and was first flight tested in the Dutch Air Force F-16. The Viper 3 exploits the visor projection scheme common to HMDs and employs multiple-folded optical paths to carry the imagery from a pair of 18-mm I^2 tubes to the pilot's spherical visor. This provides the pilot with an unobstructed binocular 40° FOV NVG capability on his see through visor. The I^2 tubes are mounted on the sides of the helmet, to provide the best possible balance for low fatigue and safe ejection. The helmet is considered suitable for loads of up to 5-6Gs.

An important feature of the optical design of the Viper 3 is that the addition of a dichroic beamsplitter to one of the mirrors in the optical path between the image intensification tubes and the visor allows the addition of a CRT to the Viper 3 design so that the system can become a combined projection HMD and NVG package, with the addition of a CRT and head tracking sensors. The addition of a CRT adds some weight but improves the center-of-mass of the overall system. The Viper 3 design solves the principal problems associated with conventional clip-on ANVIS.

There was also a limited development of a Viper 4 in the late 1990's, which was an extension of the Viper 2; it was extensively flown on VISTA F-16 and used for JSF development trials. Both CRT and flat panel display versions were produced.

Crusader (United States, United Kingdom)

The late-1990s Crusader HMD (Figure 3-20) was part of a technology development/ demonstrator program aimed at providing helmet solutions that can be applied into several fixed- and rotary-wing applications while at the same time maintain the protection levels and life support integration of current in-service helmets. The program was coordinated by the U.S. Navy, who very early-on expressed strong interest in the two-part helmet concept.

The Crusader HMD is a binocular, visor-projection design, has a 30 by 40 degree partial-overlap FOV, and incorporates dual, integrated camera-coupled I^2 tubes. The visor projection design is based on off-axis holographic optics, and provides unobstructed see-through vision with an eye relief of 76mm and extremely well balanced center-of- gravity. The Crusader system utilized dual, miniature solid state displays with a resolution of 1024 vertical by 1280 horizontal. The Crusader HMD is capable of presenting binocular on-helmet I^2 video, aircraft-provided FLIR video, and the merged, "sensor fusion" combination of these, all with both flight and fire-control symbology added.

TopSight (France)

Rather than designing an HMD around an existing helmet shell, Thales Avionics (Vélizy-Villacoublay, France), (at the time, Sextant Avionique) teamed with Intertechnique to design a new helmet system integrating the vision system with the oxygen positive pressure breathing and full nuclear, biological, and chemical (NBC) protection. The futuristic appearance of these helmets results from the use of a flush external face guard, contoured such as not to obstruct the pilot's FOV yet to fully cover the oxygen mask.

The TopSight (previously known as Opsis) (Figure 3-20), was evaluated originally on the Mirage 2000 fighter and subsequently has been used on both the Mirage and the next-generation multirole Rafale fighters. The TopSight is a day-only helmet, configured for air-to-air missions.

The TopSight uses a modular approach. The headgear includes two line-replaceable units: a) the basic helmet, with a custom-fitted form liner and b) a removable Day Display Module, that projects symbology on the pilot's visor for target acquisition and designation; depending on the mission, this module can be replaced by a Night Vision Module (ejection-compatible), or a Double Visor Module (for conventional helmet use).

Designed primarily for target acquisition and designation in support of the Mirage 2000 and Rafale, the air-to-air version is a monocular visor projection display with 20° FOV and 60- mm eye relief. It uses a 0.5-inch diameter CRT in stroke-only symbology, generated from target and aircraft parameters. The fully integrated system, including the oxygen mask, has a head-supported weight of 1.45 kg (3.2 lbs).

TopNight

The TopNight (Figure 3-20) is a TopSight helmet configured for air-to-ground and night mission for the Rafale fighter. It adds to the TopSight an image-intensified charge-coupled device (I^2CCD) camera and binocular display capability. It also adds FLIR image capability from an aircraft sensor or a night-vision image intensified image from the helmet-mounted CCD. The pilot can switch between the external FLIR and I^2CCD sensors. There is also the option of presenting an image received from an outside video source.

The TopNight has a binocular display with a 40- x 30-degree FOV and 60-mm eye relief. It uses two ½-inch diameter CRTs. Aircraft and targeting data are displayed both in stroke (symbology) and raster video imagery (IR, image-intensified tubes [I^2T] and television [TV]). The fully integrated assembly, including the oxygen mask and the I^2T, has a head-supported weight of 1.8 kg (4 lbs).

Joint Helmet Mounted Cueing System (JHMCS)

Following Joint Mission Element Needs Statement (JMENS) signed by the U.S. Air Force and U.S. Navy in mid-1994, the Joint Helmet Mounted Cueing System (JHMCS) (Figures 3-10 and 3-20) became the first joint office project. The JHMCS was developed over the period 1996-99 by Vision Systems International (VSI),[7] San Jose, CA, and is deployed on F-15, F-16 and F/A-18. VSI was formed in 1996 as a joint venture between Rockwell Collins (San Jose, CA) and Elbit Systems (Haifa, Israel) to address HMD opportunities for fixed-wing applications. The JHMCS is a multi-role system that enhances pilot situation awareness and provides head-out control of aircraft targeting systems and sensors.

The JHMCS uses visor projection design with a ½-inch CRT. It is monocular (right eye only), provides only daytime stroke symbology, uses an electro-magnetic tracker, and has a 20° FOV.

In May 2003, VSI was selected to develop a dual-seated version of the JHMCS so that both pilots, in a two-seater fighter, can share information. Deliveries of the modified version started in early 2007 for the Navy's two-seat F-18F. In a dual-seat aircraft, each crewmember can wear a JHMCS helmet, perform operations independent of each other, and have continuous awareness of where the other crewmember is looking.

The JHMCS can best be described as the offspring of the Elbit Systems Dash 3, the Kaiser Electronic Agile Eye and the VCATS HMDs. Unlike the embedded Dash, the JHMCS is a clip-on package.

The system provides low-weight, optimized center-of-mass with in-flight replaceable modules to enhance operational performance – including the ability to be reconfigured in-flight to meet night vision requirements.

The JHMCS has been introduced with the main goal of slaving the AIM-9X GEN-4 air-to-air Sidewinder Missile to the pilot line-of-sight; this will provide "first look, first shot" capability when employed with high off-boresight weapons and under high-G conditions. Production representative units were delivered in mid 1998, operational tests started in 1999 (first flight test took place in January) on an Air Force F-15 Eagle and a Navy

[7] VSI is a joint venture company between EFW, Inc. of Ft. Worth, Texas and Rockwell Collins, San Jose, CA.

F/A-18 Hornet and production deliveries commenced in 2000. It is used with the HGU-55/P helmet in F-15, F-16 and F-18 fighters.

VSI was authorized to begin full scale JHMCS production in January 2004; by January 2006 VSI advertised the delivery of the 1000th JHMCS helmet. A year later VSI had delivered over 1400 units to 14 nations.

A current list of international customers by fighter aircraft deployment includes:

- F-15 – U.S. Air Force and Air National Guard, Korea
- F-16 – U.S. Air Force and Air National Guard, Belgium, Chile, Denmark, Greece, Netherlands, Norway, Oman, Poland, Turkey
- F/A-18 – U.S. Navy, Australia, Canada, Finland, Switzerland

The U.S. Navy is pursuing an approach to integrate night vision capability into the JHMCS. The goal is for a 40-degree FOV, a typical value for a binocular NVG system. The U.S. Navy would prefer for this design to employ a modular wide-FOV system, such as the panoramic NVG that could increase FOV to as much as 100 degrees by using four I^2 tubes, all of which are slightly shorter and lighter than previous ANVIS-9 version tubes, reducing head strain under increased G-forces. The idea is to inject symbology into the optical train of one of I^2 tubes worn as traditional NVGs.

Scorpion Helmet Mounted Cueing System (HMCS) (United States)

The Scorpion™ HMCS (Figure 3-21) was developed by Gentex Corporation (Simpson, PA) for targeting pod, gimbaled sensor or high off boresight missile cueing mission scenarios. It was designed to interface with existing U.S. Pilot Flight Equipment (PFE), standard oxygen mask variants, Life Support Equipment (LSE) and current fixed-wing NVGs (AN/ANVS-9).

The Scorpion uses a low profile, SVGA color display. In the case of the Gentex HGU-55/P flight helmet, the compact optical element is mounted on the standard NVG helmet attachment. In day mode operation, the ANVIS Day Visor (ADV) is mounted on the helmet NVG jet mount via a ball-detent mechanism. In night operation, the ADV is replaced by the NVGs, which are located directly in front of the display optical combiner. The NVG's night image is viewed through the combiner, providing the pilot with fused NVG scene and color symbology.

The Scorpion also utilizes a low profile, high speed magnetic tracker system to track pilot head position.

The notable discriminators for Scorpion include:

- Left or right eye monocular
- Field of View (FOV): 26° x 19.6°
- Head-supported weight: 2.8 ounces (80 grams)
- Compatible with most visor types
- Compatible with laser eye protection and corrective spectacles
- Ejection system compatible

Scorpion is scheduled to commence operational testing by the US military at the U.S. Air Force / Air National Guard Flight Test Center (Edwards Air Force Base, CA) in 2008.

Figure 3-21. Scorpion Helmet Mounted Cueing System (Gentex Corporation),

Typhoon Integrated Display Helmet (IDH) (United Kingdom)

The Typhoon Head Equipment Assembly (HEA) Integrated Display Helmet (IDH) (Figure 3-20) displays night vision and off-axis cueing information. Selected for the Eurofighter program, the IDH provides 24-hour, all-weather, and all-altitude operation over the full combat profile envelope. Capabilities include weapon/sensor slaving with real-world overlay of flight information, target cueing and night vision.

The system uses a two-part helmet design, with a single size helmet being custom fitted to individual pilots and designed to cover the 5-95th percentile anthropometric range. The helmet provides laser and NBC protection. The helmet operates in conjunction with an optical head tracker, providing low latency head position solutions and eliminating the need for cockpit mapping. It uses dual high-resolution miniature CRTs in stroke, raster and mixed modes to provide a 40° FOV with full overlap, a 15-mm exit pupil, and a 50-mm eye relief. The night vision cameras use two Omni 4 GEN-3 I^2 tubes, capable of operation down to 0.5 millilux) and are detachable.

The helmet employs a dual visor configuration, a clear blast/display visor for night operation and a glare/ laser eye protection visor for day operation.

While the exact location of the I^2 tubes on the side of the helmet is still an issue, this approach will improve helmet dynamic performance, by moving the center-of-mass backward as compared to standard in-front-of-the-eyes I^2 tube mounting. Because the distance between the I^2 tubes exceeds the normal separation distance of the two eyes, the pilot may experience hyperstereopsis. This phenomenon results in objects viewed at close distance appearing closer than in reality, which can cause false cues (Kalich et al., 2007). Flight tests have showed that these effects are perceptible when distance to ground (or objects) is less than about 1,000 feet.

Helmet Mounted Display System (HMDS) (United States)

The Helmet Mounted Display System (HMDS) (Figure 3-20) is being developed for the F-35 Joint Strike Fighter (JSF) by VSI. It has completed all required safety of flight tests, allowing in-flight seat ejections up to 450 KEAS (knots equivalent air speed). It has demonstrated structural integrity to 600 KEAS as a critical risk mitigation step towards full flight certification. The HMDS had its maiden flight on 4/10/2007 on the 10th test flight of the F-35 JSF.

The HMDS provides the pilot video with imagery in day or night conditions combined with precision symbology to give the pilot enhanced situation awareness and tactical capability. For tactical fighter jet aircraft, the F-35 JSF will be the first to fly without a dedicated HUD, with the HMDS providing this functionality.

The HMDS uses the same symbology implemented in the JHMCS. The CRT display in the JHMCS has been replaced by two 0.7-inch diagonal SXGA resolution AMLCDs. The HMDS provides a FOV of 40° (H) x 30° (V).

Military HMD programs: Rotary-wing platforms

While fixed-wing HMD applications abound, the HMD owes its increasing acceptance to rotary-wing aviation. The helicopter environment does not require the HMDs to contend with the demands of high-G maneuvers or ejection with its issue of wind blast. This does not imply that HMD designs for rotary-wing applications are easier. Indeed, the requirements for a wider FOV and increased resolution driven by the common-place nap-of-the-earth (NOE) flight profiles of military helicopters are difficult ones.

Table 3-3 presents a partial summary of the more notable experimental, prototype, fielded and future HMD rotary-wing programs. It followed by summaries of select HMD programs. Many of these HMDs are depicted in Figure 3-22. Many of the programs involved a number of contracts with various commercial HMD developers playing differing roles. Many of the programs also were multi-national in scope. The country of development listed in Table 3-3 and ensuing program descriptions generally is based on the initial developmental phase.

Integrated Helmet and Display Sighting System (IHADSS) (United States)

The first fully integrated head/helmet-mounted display, the IHADSS developed by Honeywell in late 1970's, and was acquired by (2000) and now manufactured by EFW (Figure 3-22), was fielded by the U.S. Army in the AH-64 Apache helicopter and is still in production.

Historically, the goal of aviation helmet design has been to primarily provide impact and noise protection to the user. In 1981, the U.S. Army fielded an advanced attack helicopter that required a new helmet concept in which the role of the helmet was expanded to provide a visually-coupled interface between the aviator and the aircraft. This new combined helmet and display system, the IHADSS, uses a helmet fitted with infrared (IR) head tracker detectors and a monocular display. The IR head tracker allows a slewable FLIR imaging sensor, mounted on the nose of the aircraft, to be slaved to the aviators head movements. Imagery from this sensor is presented to the aviator through the helmet-mounted display.

The IHADSS HMD consists of a fully functional flight helmet to which the monocular display is mounted. The display can present to the pilot's eye combinations of aircraft symbology (e.g., heading, torque, altitude, etc.), a targeting crosshair, and pilotage imagery that originates from the FLIR sensor mounted on the nose of the aircraft. The IHADSS has also been used by Boeing on OH-58D Kiowa and by Agusta, on the A-129 Mangusta.

The IHADSS' major capabilities include:

- Slaves turreted weapons, missile seekers, and gimbaled night vision sensors to the pilot's line-of-sight;
- Displays real-world-sized video imagery from night vision sensors directly in front of the pilot's eye and overlays flight information and fire control symbology over the video imagery;
- Can be operated either independently from each cockpit or cooperatively from both cockpits while allowing cueing between the aircraft's crew members; and
- Enables NOE navigation by pointing a night vision sensor with natural head movements only.

Table 3-3.
Summanry of selected rotary-wing HMD programs.

Time frame	Program	Country	Platform	Developer	Program status	Notes
1970s	IHADSS	USA	Rotary-Wing Apache	Honeywell	Fielded	First integrated HMD
Early to mid 1980s	Wide-Eye	USA	Rotary-Wing Various	Rockwell Collins	Experimental	
Mid to late 1980s	Eagle Eye	USA	Rotary-Wing	Night Vision Corporation	Prototype	
Late 1980s	AN/AVS-6 ANVIS	Multiple	Rotary-Wing Various	ITT	Fielded	
Late 1980s	MONARC	USA	Rotary-wing	Honeywell	Prototype	
1990s	HIDSS	USA	Rotary-Wing Comanche	Rockwell Collins	Prototypes	The Comanche program was cancelled in 2004
1990s	MiDASH	Israel	Rotary-Wing Various	Elbit Systems	Fielded	
Late 1990s	Knighthelm	UK	Rotary-Wing Various	BAE Systems	Fielded	

Table 3-3.(continued)
Summanry of selected rotary-wing HMD programs.

Time frame	Program	Country	Platform	Developer	Program status	Notes
Mid 1990s	Crusader	US/UK	Fixed- & Rotary-wing	Gentex/ BAE Systems/ Thales	Experimental	Technology demonstrator
Late 1990s	TopOwl	France	Rotary-Wing Euro helicopter	Thales	Fielded	Selected for the AH-1Z Cobra
Mid 1990s	ANVIS/HUD-7	Israel	Rotary-Wing Various	Elbit Systems	Fielded	
Mid 1990s	ANVIS/HUD-24	Israel	Rotary-Wing Various	Elbit Systems	Fielded	
Late 1990s/Early 2000s	VCOP	USA	Rotary-Wing Various	Microvision	Experimental	Technology demonstrator
Early 2000s	HeliDash	Israel	Rotary-Wing Miscellaneous	Elbit Systems	Fielded	
Mid 2000s	MIHDS Air Warrior Block 3	USA	Rotary-Wing Various	Microvision	Development	Spectrum SD 2500
Late 2000s	Q-Sight	UK	Rotary-Wing Various	BAE Systems	Experimental	Technology demonstrator

Figure 3-22. Current and future rotary-wing HMD programs.

Primary IHADSS performance characteristics include:

- Image brightness compatible with 2,000-foot-Lambert (fL) background luminance scene; it lacks luminance performance required for optimal gray-scale operation during most daylight missions
- Monocular, right eye only, 1-inch diameter CRT image source
- Display FOV: 40° (H) by 30° (V)
- Exit pupil: circular, 10 mm in diameter
- Video format: Raster only 525 to 875 lines (auto line lock), compatible with GEN-1 FLIR
- Optical eye relief: 10 mm

User performance of the IHADSS is well documented (Rash, 2008). Its visually demanding monocular design has been successful in its deployment in the AH-64 Apache helicopter but has been plagued since initial fielding by frequent pilot reports of visual symptoms and complaints (Hale and Piccione, 1989; Behar et al., 1990). However, during most recent challenge of combat in Iraq, these reports have decreased (Hiatt et al., 2004; Heinecke et al., 2008).

Wide-Eye™ (United States)

The Wide-Eye, ™ designed by Kaiser Electro-Optics, San Jose, CA, and first conceived in the 1980s, was a integrated binocular HMD with retractable combiners for day and night use. It had two 1-inch CRTs as well as I^2 tubes. A modular approach was employed where the optical subsystem is detachable and remains with the aircraft. The system consisted of the helmet, display electronics unit, head-tracker and boresight reticle control unit.

The Wide-Eye™ was a partial-overlap design. Each optical channel has a monocular FOV of 40°; with a 50% overlap, the binocular FOV is 40° (V) by 60° (H) (Zintsmaster, 1994). This system was the precursor to Kaiser Electro-Optics's SIM EYE™ XL 100A design (Kaiser Electro-Optics, 2007).

Tactical-Air Night Vision Display System (Eagle Eye) (United States)

The Tactical-Air Night Vision Display System, built by Night Vision Corporation, and commercially known as Eagle Eye,™ was a low-profile, helmet-mounted, image intensifying system. It was a self-contained system, consisting of two GEN-3 I^2 tubes, folded optics beamsplitters, external housing, and integrated power supply. The folded optical path was designed to allow the I^2 sensors to be located slighted below and to the side of each eye, making the total separation between centers approximately 126 mm (5 inches). The effective interpupillary distance (IPD) was approximately twice the normal 64-millimeter (mm) value. Like ANVIS, the nominal FOV was 40 degrees and fully overlapped. The objective lenses could be focused from 11 inches to infinity. While there was no eyepiece optical adjustment, eyepiece lenses could be inserted in 2-diopter increments to compensate for spherical refractive error ranging from - 6 to +2 diopters. Adjustments included fore-aft, vertical, tilt, and IPD. The Eagle Eye had a limited production in the 1980s.

Aviator's Night Vision Imaging System (ANVIS) (United States)

The ANVIS (Figure 3-22) is by far the most widely used HMD in the world. The ANVIS is a combined sensor/display optics package that mounts unto existing aviation helmets by means of a visor assembly mounting bracket. Over the last two decades, improvements in the I^2 technology used in the ANVIS have given rise to a number of generations and models, all of which loosely referred to as the ANVIS. In the U.S. Army, all ANVIS are AN/AVS-6 models, with current fielded versions identified as types 4 to 6 that define when they were procured and with corresponding performance enhancements. The ANVIS-9 designation is one used by the U.S. Navy and Air Force. It has identical performance but the helmet mount is slightly longer and at a different tilt in order to be compatible with Air Force and Navy helmets. The ANVIS-9 also has an internal filter that blocks more of the visible spectrum (related to lighting compatibility issues). The ANVIS is a binocular, 40°, 100% overlap system using GEN-3 I^2 tubes, which being head-mounted, does not require an additional head tracking system.

Typical ANVIS-6 optical characteristics include:

- Focus range: 28 cm (11 inches) to infinity
- Magnification: Unity (1X)
- 27-mm effective focal length objective (f/1.23)
- Resolution: >1.3 cycles/milliradian (cy/mr)
- Brightness gain: minimum 2000x (5,500X for newer versions)
- Diopter eyepiece focus adjustment
- Interpupillary distance (IPD) adjustment: 52-72 mm

The ANVIS housing can be flipped up or down and has an 11-15G breakaway threshold. A tilt adjustment of approximately 10º is provided. There is a minimum vertical and fore/aft adjustment range of 25 mm. They operate off of a single lithium or two “AA” batteries. A dual battery pack is Velcro™ mounted on the rear of the helmet to improve the CM. An historical summary of the ANVIS and its predecessors is provided by McLean et al. (1998).

Monolithic Afocal Relay Combiner (MONARC) (United States)

The Integrated Night Vision System (INVS), built in the late 1980s and early 1990s by Honeywell, Inc., Minneapolis, Minnesota, and commercially known as the Monolithic Afocal Relay Combiner (MONARC), consisted of a helmet subsystem, a binocular image display system, and provisions for a magnetic head tracker. The helmet included a visor, energy liner, retention system, communications, thermoplastic liner, image display, magnetic receiver mounts, and electrical interfaces. Imagery, from binocular I^2 sensors and dual (binocular) CRTs, with added symbology was designed to be displayed through the imaging system which consisted of separate modules mounted to each side of the helmet. The modules were powered by an ANVIS-style battery pack. Each module contained a GEN-3 I^2 tube, CRT, objective and relay optics and beamsplitter. (Note: The MONARC combiner used the principle of total internal reflections to relay the image from the CRT image source to the eye.) The I^2 sensors were located beside and slightly above the user's eye, making the total separation distance between sensors (and effective IPD) approximately 254 mm (10 inches) (4X normal IPD). The objective lenses could be focused from 6 meters to infinity. The vertical and lateral IPD positions of each module could be adjusted independently, but there was no fore-aft or tilt adjustments. This system provided a nominal 35°, fully overlapped FOV.

Helmet Integrated Display Sight System (HIDSS) (United States)

In the 1990s, the U.S. Army was developing the next-generation armed reconnaissance helicopter, the RAH-66 Comanche. Integral to this aircraft was an HMD designed by Kaiser Electronics, San Jose, CA. The HMD was the Helmet Integrated Display Sighting System (HIDSS) (Figure 3-22). While the Comanche program was cancelled by the Army in February, 2004, the HIDSS development program led to a number of interesting and useful concepts in HMD design.

The initial HIDSS design was based on the Wide-Eye integrated binocular design. It originally provided a 40° (V) by 40° (V) FOV with 50% partial-overlap. Ultimately, the FOV specification became at 30° (V) by 52° (H), matching the anticipated GEN-2 FLIR sensor, with at least 30% overlap. The first HIDSS design incorporated two 1-inch diameter CRTs. While image quality was found to be acceptable, the addition of a second CRT (as compared to the IHADSS single CRT) pushed the total head-supported weight beyond the Army’s acceptable safety limits (Harding et al. 1998). A follow-up HIDSS design replaced the CRT image sources with miniature LCDs.

The HIDSS also used a modular approach, partitioning the system into an Aircraft Retained Unit (ARU) and a Pilot Retained Unit (PRU). The ARU was detachable from the helmet and remained stowed in the aircraft at all times; the PRU was a custom-fitted helmet and was retained by the pilot.

The technical performance goals for the HIDSS program included:

- SXGA Resolution: 1280 x 1024 pixels
- Luminance: 1500 fL, at the eye
- Modulation transfer function (MTF): 8% (H and V with one line-on/one line-off
- Exit pupil: 15 mm
- Eye relief: 25 mm
- Head-supported mass: Not to exceed 2.4 kg (5.3 lbs)

Modular Integrated Display and Sight Helmet (MiDASH) (Israel)

The MiDASH (Figure 3-22), manufactured by Elbit Systems Limited, Haifa, Israel, helmet, was designed to provide attack and reconnaissance helicopter pilots with wide-FOV, see-through binocular night imagery, flight information and line-of-sight cueing for day and night operation (Elbit Systems, 2004).

MiDASH comprises a standard helmet shell with a personal fitting device. The left and right optical modules are referred to as Helicopter Retained Units (HRUs) and are attached to the helmet by snap-connectors.

System performance specifications:

- Binocular, night imagery FOV: 50°H x 40°V (partial-overlap)
- Symbology FOV: 30° circular
- See-through transmission: >50%
- Eye relief: >50 mm
- Night vision: "Super GEN '98" or GEN-3
- Total mass (night operation): 2.2 kg (4.9 lbs)

Knighthelm (United Kingdom)

The Knighthelm (Figure 3-22), manufactured by BAE Systems, is a first-generation HMD featuring a modular (two-part)design, with a basic form-fitted helmet designed specifically for HMD applications. The display's image sources and optical components are integrated into the helmet such that the fundamental properties of the helmet (e.g., protection, weight, CM) were not compromised (White and Cameron, 2001). The Knighthelm HMD provides a full day/night mission capable system in a binocular, 40° FOV, full-overlap configuration.

Knighthem provides night vision capability via either imagery from an aircraft-mounted FLIR sensor or a pair of GEN-3 I^2 tubes integrated into the helmet. The FLIR imagery, combined with flight and weaponry symbology, is projected onto the two combiners.

A dual-visor system is fitted to the display module: a clear visor (Class 1) that can be alternated with a laser protection visor and a neutral density visor (Class 2) for glare protection. For ease of replacement the visors are mounted on quick release pivot assemblies.

The Knighthelm's initial 1990's design has been refined and enhanced, as part of an extensive development program, for the German Army Tiger helicopter, and is optimized for the attack helicopter application (White and Cameron, 2001).

Major Knighthelm performance specifications include:

- Exit pupil: 15 mm
- Eye relief: 30 mm
- See-through transmission: 70%
- Symbology overlaid on image intensified or sensor imagery
    - Cursive (stroke) symbology visible in all ambient conditions
    - Selectable binocular/ monocular CRT symbology presentation
- Weight: 2.2 kg (4.9 lbs)

Crusader (United States, United Kingdom)

While there was never a formal developmental program for a rotary-wing Crusader HMD, the fixed-wing version was developed with the potential of rotary-wing use, with specific attention paid to the greater impact and penetration requirements for the HMD helmet platform. (See fixed-wing description in the *Military HMD programs: Rotary-wing platforms* section of this chapter.)

TopOwl (France)

The TopOwl™ (Figure 3-22) is manufactured by Thales, France. It has a fully-overlapped, visor projection system, capable of presenting FLIR, I^2 and synthetic imagery. The visor projection approach improves viewing of the outside world over standard HMD designs that require optical beamsplitters. This approach also allows for increased physical eye relief (>70 mm [>2.75 inches]), which reduces potential interference with the wearing of corrective spectacles. Dual I^2 sensors are located on the sides of the helmet with a separation distance of approximately 286 mm (11.25 inches) (an effective IPD of more than 4X normal). The I^2 imagery is optically-coupled to the visor. The FLIR imagery from a nose-mounted thermal sensor is reproduced on miniature CRTs (current production version) or LCDs (prototype) and projected onto the visor. In I^2 mode, it presents a 40° circular FOV; for FLIR imagery presentation, the FOV is 40° (H) by 30° (V).

The production CRT version is currently fielded on various models of the Eurocopter Tiger and Denel AH-2 Rooivalk helicopters and in use in 15 countries. It has been selected for use on the U.S. Marine Corps AH-1W Super Cobra attack helicopter.

The total weight of a fully configured production CRT-version of TopOwl has a mass of 1.8 kg (4 lbs) for day-only operations and 2.2 kg (4.8 lbs) for the nighttime configuration.

ANVIS/HUD-7 and -24 (Israel)

The major disadvantage of legacy I^2 systems (e.g., ANVIS series) is the lack of symbology. An approach to solve this deficiency is the ANVIS/HUD, developed by Elbit Systems. The first version is the ANVIS/HUD-7, which combines the standard ANVIS goggles image with aircraft flight instrumentation and computer graphics during night operation (Figure 3-22). The system can be installed on any type of helicopter. Figure 3-23 presents sample ANVIS/HUD-7 imagery consisting of symbology overlaid on I^2 imagery.

Major technical performance specifications of the ANVIS/HUD-7 include:

- FOV:
  - Night vision - 40°
  - Symbology - 32° overlaid on the night imagery without degradation to the ANVIS image
- Resolution: > 512 x 512 pixels
- Mass: <110 g (3.9 ounces)
- Compatible to GEN-2, GEN-3 and OMNIBUS I^2 systems
- Attachable to the right or left objective
- Compatible with NBC mask or eyeglasses
- Quick disconnect for safe egress

Elbit Systems Limited developed the Day/ Night ANVIS/HUD-24 from the ANVIS/HUD-7 system above, with the DAY HUD add-on module, the system projects imagery of flight information to enable head-out flight during the day time (Yona et al., 2004). By combining the standard ANVIS imagery with aircraft flight instrumentation symbology, the ANVIS/HUD offers 24-hour operational capability. The system supports two-pilot operation, with eight selectable display screens and can be installed on any type of helicopter; it is currently operational on more than 25 different platforms.

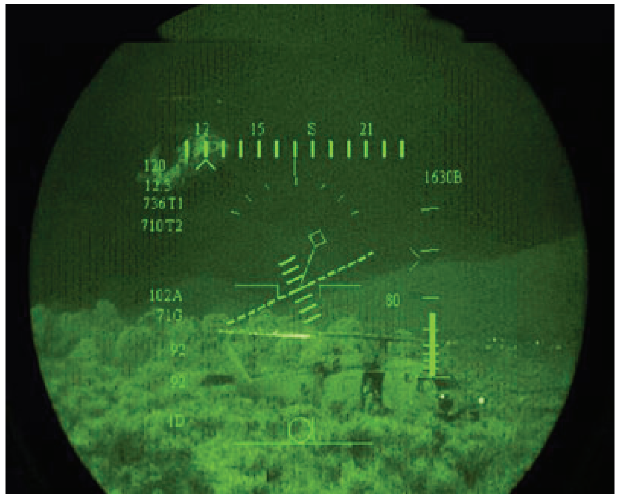


Figure 3-23. Typical ANVIS/HUD-7 imagery: Symbology overlaid on night imagery.

Performance values for night operation are identical to the ANVIS/HUD-7. The day channel performance is defined by:

- Day FOV: 25°
- See-through transmission: 36%
- Brightness: 500 fL
- Exit pupil: >12 mm
- Eye relief: >50 mm (may be used with NBC mask or eyeglasses)
- Head-supported mass: 200 grams (7.1 ounces)

EyeHUD™ (United States)

The EyeHUD™ (Figure 3-24), developed by Rockwell Collins, Cedar Rapids, IA, is a compact, light-weight monocular HMD designed as a alternative to the ANVIS/HUD. It is designed to attach to the standard ANVIS mount. Using a miniature AMLCD, its goal is to provide pilots basic HUD situation awareness capability (e.g., aircraft flight, engine performance and weapons symbology) in both day and night operations (Rockwell-Collins, 2008a) The EyeHUD™ HMD can be used with any military aviator helmet. It provides a full range of IPD and vertical adjustments while accommodating laser eye protection and aviator eyewear.

Major technical performance features include:

- Day FOV: 26° (Diagonal)
- Resolution: 800 x 600 (SVGA)
- Head-supported mass: 95 grams (2.6 ounces)
- Compatible with ANVIS Class A and B spectral response

Figure 3-24. EyeHUD.™

QuadEye™ (United States)

QuadEye™ (Figure 3-25a) was developed by Kollsman, Merrimack, NH and is an advanced Panoramic Night Vision Goggles (PNVG) providing a central 40° binocular FOV plus monocular vision of an additional 30° to either side (Figure 3-25b) (Kollsman, 2008). The impetus of this expanded FOV design is to provide a FOV similar to the normal eye's peripheral vision, thereby reducing the need to increase head movement when wearing the ANVIS. QuadEye is designed around four 16-mm I^2 tubes of which the pilot can select either only the two inner tubes or all four (panoramic) tubes. Additionally, QuadEye™ can provide HUD symbology or aircraft targeting sensor imagery using a miniature, high resolution display.

Main system performance values include:

- FOV: 100° (H) by 40° (V)
- Physical eye clearance: 32 mm
- Brightness gain: > 5,500:1
- Mass (with four I^2 tubes, display, camera): 700 grams (25 ounces)

The U.S. Army's Virtual Cockpit Optimization Program (VCOP) was a virtual cockpit simulator program. Its goal was to provide the pilot with a simulated environment where he/she could train with information such as situational awareness, sensor imagery, flight data, and battlefield information in a clear, non-confusing and intuitive manner (Moore et al., 1999; Harding et al., 2004). VCOP was comprised of six technologies:

- Full color, high resolution, high brightness HMD that incorporates Virtual Retinal Display (VRD) technology
- 3-D audio
- Speech recognition
- Situation awareness tactile vest
- Intelligent information management
- Crew-aided cognitive decision aides

Figure 3.25a. QuadEye™ (www.kollsman.com).

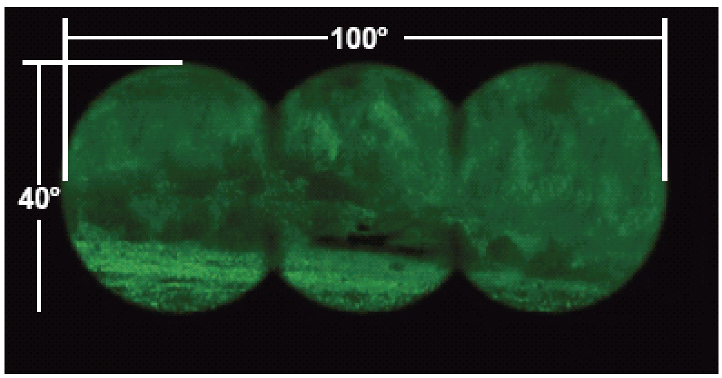


Figure 3-25b. QuadEye™ field of-view (www.kollsman.com).

Virtual Cockpit Optimization Program (VCOP) (United States)

VRD technology was invented at the University of Washington in the Human Interface Technology Lab (HIT) in 1991. Its goal was to produce a full color, wide FOV, high resolution, high brightness, low cost virtual display using miniature scanned lasers. The original VRD concept used scanning lasers to form an image directly on the retina.

Microvision, Inc., Seattle, WA, has the exclusive license to commercialize the VRD technology and was the developer of the VCOP HMD. The VRD scanning laser technology has been pursued for a number of HMD programs. HMD applications have deviated from the original VRD concept in that the scanning lasers do not scan directly on the retina but instead form an intermediate image that is viewed via an eyepiece. Figure 3-26 shows an early prototype developed under the U.S. Army's Aircrew Integrated Helmet System (AIHS) alternate image source development. Figure 3-22 shows a futuristic version of the VCOP design.

Figure 3-26. Prototype AIHS scanning laser HMD (Microvision, Inc.).

HeliDash (Israel)

HeliDash is a modular day/night display and sight helmet designed by Elbit Systems for attack, assault and utility helicopter applications. It provides the pilot with high-resolution night vision and day/night symbology. The system configuration includes electronics, clear/dark visors, a night module (ANVIS-HUD), and a day Module (DASH 20° FOV visor-projected symbology).

Modular Integrated Helmet Display System (MIHDS) (Air Warrior) (United States)

The Air Warrior program is one of a group of U.S. Army Warrior Soldier Warrior programs. General Dynamics C4 Systems (Scottsdale, AZ) is the prime contractor and system integrator for all of these systems, which additionally include Land Warrior and Mounted Warrior.

Air Warrior is intended to provide U.S. Army rotary-wing aircrew with advanced life support, ballistic protection, and NBC protection in rapidly tailorable, mission-configurable modules. Its development has in been in a 3-block format. Block 1 included the development, procurement, and fielding of a micro climate cooling system, an integrated survival gear and ballistic protection system, and a light-weight chemical and biological protection ensemble. The on-going Block 2 technology insertion phase of the program provides additional capabilities, including an Electronic Data Manager and an Aircrew Wireless Intercom System. Block 3 is focused on increasing force effectiveness by improving situation awareness and survivability. The Air Warrior systems must be compatible with multiple helicopter types, including the CH-47 Chinook, OH-58D Kiowa Warrior, AH-64 Apache and UH-60 Blackhawk. It also is required to have compatibility interoperability with the Army's Land Warrior and Future Combat Systems programs.

Integral to the Block 3 phase is the development of an HMD. General Dynamic's program to provide the HMD is Modular Integrated Helmet Display System (MIHDS). The MIHDS will provide integration and interface of symbology, imaging sensors, and head-position tracking devices, permitting the aircrew a clear view of the external environment during both day and night operations.

Microvision's ™ SD2500 (Figure 3-27), a descendent of VCOP, is a candidate system for the MIHDS. The SD2500 design provides a full-color, see-through, daylight and night-readable, high-resolution (800X600 pixels) display (Microvision, 2005). This HMD is fitted for attachment to the U.S. Army's standard aviation helmet, Head Gear Unit 56P (HGU-56P), via the common Aviator's Night Vision Imaging System (ANVIS) mounting bracket.

Major performance specifications include:

- HMD type: Monocular, Color RGB
- See-through transmission: >50%
- FOV: 23º (H) x 17º (V)
- Resolution : SVGA, 800 (H) x 600 (V) pixels
- Luminance (at the eye): >1000 fL, D65 white
- Physical eye relief: > 50 mm
- Interpupillary distance (IPD) range: 29-36 mm from center

Q-Sight (United Kingdom)

The Q-Sight™ (Figure 3-22) is being developed by BAE Systems. Its design employs holographic wave-guide technology. Weighing less than 4 ounces (113 grams), it has no bulky projection optics and offers an exceptional center-of-mass.

Q-Sight's miniature display is easily adaptable to any standard helmet as either a left- or right-side configuration (at approximately 25 mm), allowing the pilot to choose his or her dominant eye. A binocular configuration also is available.

Symbology and/or video can be displayed to provide the pilot with eyes-out operation (Figure 3-28). In day (high-ambient-light) conditions, a dark visor can be deployed to improve the image contrast. Q-Sight is designed to be compatible with the current NVGs. Operation at night is achieved by attaching the NVG and deploying in the normal manner. The Q-Sight display is located in its own mount and positioned behind the NGV eyepiece (BAE Systems, 2007). Flight demonstrations of the Q-Sight system are planned for late 2007 and early 2008.

Major performance specifications include:

- FOV: 30°, monocular
- Luminance: 1800 fL
- Contrast ratio 1.2:1
- Exit pupil: > 35 mm
- Eye relief: > 25 mm
- Power consumption: <5 watts, head-mounted
- Head-supported mass: < 113 grams (4 ounces)

Military HMD programs: Mounted and dismounted

In the development and application of HMD technology, aviation has led the way. However, in the early 1990s, the potential of HMDs for mounted and dismounted Warfighters was recognized fully. This has led to a number of development programs that focused on the differing requirements that must be imposed on HMDs intended for ground applications. Not surprisingly, I^2 technology has been the sensor technology of choice in these non-aviation designs. However, the fundamental characteristics of these ground-based HMDs are the result of decades of lessons learned from aviation-based HMDs development programs.

Figure 3-27. Spectrum™ SD2500 (Microvision, Inc.).

Figure 3-28. View of symbology through Q-Sight (BAE Systems).

As HMDs move from air to ground, there will be important economic considerations. While HMDs have been fielded in both fixed- and rotary-wing aircraft for decades, their quantity have been small. This number will change drastically as HMDs are issued to every Warfighter along with his/her weapon and boots. As with any system, the larger the production demand, the smaller the unit cost.

Table 3-4 presents a summary of the more notable experimental, prototype, fielded and future HMD programs for mounted and dismounted applications and is followed by summaries of respective HMD programs.

Combat Vehicle Crew (United States)

The Combat Vehicle Crew (CVC) HMD (Figure 3-29) program, initiated in 1992, was a research and development effort to develop a high resolution, flat panel-based HMD for the Army's M1 A2 Abrams main battle tank (Nelson, 1994).

Table 3-4.
Summary of selected mounted and dismountedHMD programs.

Time frame	Program	Country	Platform	Developer	Program status	Notes
Early 1990s	Combat Vehicle Crew	USA	M1 A2 Abrams Tank	Honeywell, Inc	Development	
Mid 1990s	Land Warrior	USA	Wearable	Rockwell Collins	Development	ProView SO-35
Late 1990s	Mounted Warrior (MWSS)	USA	Stryker Combat Vehicle	Rockwell Collins	Development	ProView SO-35
Late 1990s	DHTVS	USA	Combat and Combat Support Vehicles	Rockwell Collins	Limited fielding	
Early 2000s	NOMAD	USA	Stryker Combat Vehicle	Microvision, Inc.	Limited fielding	

Figure 3-29. Combat Vehicle Crew (Girolamo, 1997).

The CVC HMD was intended to provide a head-out HMD for tank commanders; it also would allow commanders to track near-range threats, survey the proximal terrain and avoid collision (Girolamo, 1997). The initial design was developed by Honeywell, Inc. (Minneapolis, MN), using a monochrome AMLCD panel that provided a 40° FOV at VGA (640 x 480 pixels) resolution. In 1994, the display was upgraded to SXGA (1280 x 1024 pixels) resolution for integration in the CVC HMD system used in both the Abrams tank and the Bradley fighting vehicle. The system maintained a 40° FOV and was used to project thermal imagery and tactical battlefield information. After an initial operational test, the program was discontinued in 1997.

Land Warrior (United States)

The Land Warrior program is an integrated fighting system for individual infantry soldiers which gives the soldier enhanced tactical awareness, lethality and survivability (SPG Media, 2008). The systems included in Land Warrior are the weapon system, helmet (HMD), computer, digital and voice communications, positional and navigation system, protective clothing and individual equipment. The Land Warrior system will be deployed by infantry and combat support soldiers, including rangers, airborne, air assault, and light and mechanized infantry soldiers.

The Land Warrior program is one of a group of Army Warrior Soldier Warrior programs for which General Dynamics C4 Systems (Scottsdale, AZ) serves as the prime contractor and system integrator.

The Land Warrior program was initiated in 1994. Raytheon Systems, (then Hughes Aircraft Company) was the engineering developer. Plans were drafted to build an Initial Capability (formerly Land Warrior Block 1) and then a Land Warrior Stryker Interoperable (formerly Land Warrior Block 2). In 2003, General Dynamics Decision Systems (now General Dynamics C4 Systems) was selected to enhance the Land Warrior system with integration to the U.S. Army digital communications, interoperability with the Stryker Brigade Combat Vehicle (SPG Media, 2008).

The helmet system is known as the Integrated Helmet Assembly Subsystem (IHAS). It provides required ballistic protection while serving as a platform for a helmet-mounted computer and sensor display, which serves as the Warfighter's interface to digital battlefield. Through the HMD, the Warfighter can view computer-generated graphical data, digital maps, intelligence information, troop locations and imagery from a weapon-mounted Thermal Weapon Sight (TWS) and video camera. This new capability allows the soldier to view around a corner, acquire a target, then fire the weapon without exposing himself, beyond his arms and hands, to the enemy. The thermal images are presented on the HMD.

Currently, the Land Warrior HMD is the Rockwell Collins ProView™ S0-35 (Figure 3-30). It is a monocular design and uses the eMagin's (East Fishkill, NY) full color SVGA active-matrix OLED (AMOLED) display. Major technical performances parameters include:

- Luminance: 0.1-30 fL
- Resolution/FOV:
    - SVGA resolution (800 x 600): 28° x 21° (35° diagonal)
    - VGA resolution (640 x 480): 22° x 17° (28° diagonal)
- Eye relief: >25 mm (Eyeglasses compatible)
- Exit pupil: Non-pupil forming system
- Image source type: Full-color AMOLED 800 (x3) pixels x 600 lines
- Mass: 67 grams (2.4 ounces) Display module (w/out mount), 145 grams (5.1 ounces) (with helmet mount)

Figure 3-30. The Land Warrior HMD concept and the Rockwell Collins ProView™ S0-35 (Rockwell-Collins, 2008b).

The U.S. Army merged the Land Warrior program with the Future Force Warrior (FFW) program in 2005 with General Dynamics C4 Systems as prime integrator. FFW is a Science and Technology initiative to develop and demonstrate innovative capabilities for Future Force Soldier systems. The FFW is scheduled to be fielded in 2010 and will be followed, in 2020 by the Vision Future Force Warrior. FFW is designed to provide a ten-fold increase in lethality and survivability of the infantry platoon. In May 2007, a comprehensive assessment of the Land Warrior (and Mounted Warrior) systems conducted jointly at the U.S. Army Infantry Center, Fort Lewis, WA. More than 400 soldiers of the 4th Battalion, 9th Infantry Regiment, 4th Stryker Brigade Combat Team, 2nd Infantry Division participated. The battalion was equipped with 440 Land Warrior Systems and 147 Mounted Warrior Systems. Following this test and evaluation, an initial set of Land Warrior systems was deployed with the 4-9 Infantry Stryker Battalion in late 2007.

Mounted Warrior Soldier System (United States)

The Mounted Warrior Soldier System (MWSS) (Figure 3-31) is another major component of the Army's Soldier as a System initiative (with Land Warrior and Air Warrior). It is envisioned as an integrated "system of systems" designed to improve the survivability, lethality, and combat effectiveness of Stryker-mounted crewmen. The MWSS leverages capabilities being developed in other warrior programs, such as Land Warrior, Air Warrior and Future Force Warrior.

Figure 3-31. Mounted Warrior Soldier System (MWSS) concept.

Rockwell Collins has been selected by General Dynamics C4 Systems to provide HMDs for Increment I of the Mounted Warrior Helmet Subsystem (HSS) program. The recommended HMD of choice is the ProView S0-35™ monocular. This selection illustrates design re-use opportunities across General Dynamics' warrior programs since Rockwell Collins' HMD is currently qualified for use in the Army's Land Warrior program.
The HMD provides the wearer with the capability to select and view display of information from one of three existing video sources within the Stryker:

- Driver's Vision Enhancer (DVE),
- Remote Weapon System (RWS) via the Video Display Terminal (VDT),
- Force XXI Battle Command, Brigade and Below (FBCB2) display.

In an interesting subsequent development, in September 2006 Microvision, Inc., has been awarded a contract by General Dynamics C4 Systems to supply full-color, daylight readable, see-through HMDs as part of the U.S. Army's Mounted Warrior HMD Improvement Program. Microvision, Inc., will use its scanning-laser technology. The improvement program, managed by the U.S. Army's Project Manager for Soldier Warrior under Program Executive Office Soldier, is looking for reduced size, weight, and power requirements. The contract specifies the development, design, verification, testing, and delivery of ten full-color display units for evaluation by mid-2007.

Drivers Head Tracked Vision System (DHTVS) (United States)

In the late 1990s, the U.S. Army developed a system known as the Drive Head Tracked Vision System (DHTVS) as an aid to drivers of combat and combat support vehicles (Casey, 1999). The system consisted of:

- Uncooled, gimbaled FLIR sensor
- Flat panel display
- Electronics box
- HMD

The HMD had a biocular non-see-through design that mounted onto the driver's helmet. The 30° (V) by 40° (H) FOV of the HMD matched the sensors FOV. The displays were XGA AMLCDs. An IPD adjustment was provided, and the oculars could be swung up out of the driver's field-of-vision.

NOMAD Augmented Vision System (United States)

The NOMAD Augmented Vision System (Microvision Inc.) (Figure 3-32) was developed for use in ground vehicles and has been fielded on Stryker vehicles deployed in Operation Iraqi Freedom (OIF). This HMD allows vehicle commander to stand (down) in his hatch and retain a view of the outside world, hence maintaining situation awareness. Similar NOMAD displays have been designed for use in maintenance, repair and overhaul applications. Being able to present vehicle and equipment repair checklists, parts lists, and schematics and diagrams in a head-up format right at the repair site can increase efficiency and reduce downtime (Rash, 2006b).

The NOMAD class of displays uses a scanning laser display that provides 800 by 600 pixels of resolution. Its manufacturer-cited specifications include:

- Luminance: Up to 1,000 fL
- Shades of grey (contrast metric): 32
- Mass: < 200 grams (7 ounces)
- Operating temperature range: 32-113° F (0-45°C)

Figure 3-32. NOMAD (Microvision, Inc.).

Military HMD programs: Simulation and training

Realistic training and mission rehearsal enhance crew proficiency, mission success and, most importantly, crew survivability. As a consequence of increased U.S. military involvement around the world, the military expects significant future growth in the demand for deployable virtual reality trainers. The effect of the rapid advancement in networking capability, both local-area and satellite-based wide area, computer and display technologies, has resulted in networked deployable trainers scattered around the world that allow U.S. and coalition military personnel to train collectively, in a synthetic, but realistic environment. Realism, necessary for training effectiveness, has been greatly enhanced through the use of very accurate terrain maps generated from aerial and satellite photographs. Collective training, encompassing joint aviation, naval and ground vehicle simulators based in different parts of the world, can today be performed in the same virtual battle space as the result of this networked simulation capability. Visual display capability consistently has been a critical element in successfully training military aviators.

In addition to the VCOP HMD, two major examples of U.S. aviation simulators are the Aviation Combined Arms Tactical Trainer – Aviation Reconfigurable Manned Simulator (AVCATT-A) and the Flight School XXI simulator.

Aviation Combined Arms Tactical Trainer – Aviation Reconfigurable Manned Simulator (AVCATT-A) (United States)

The AVCATT-A is a mobile, transportable, virtual simulation training system that provides Army aviation with the capability to conduct realistic, high intensity training exercises and mission rehearsals for five of the Army's current and future generations of frontline helicopters—the AH-64A Apache and AH-64D Apache Longbow, the CH-47D Chinook, the UH-60 Black Hawk, and the OH-58D Kiowa Warrior. (See earlier discussion of AVCATT in Flight training section of this chapter) Each AVCATT-A unit is housed in two 53-foot-long trailers (Figure 3-33), that have been designed to be deployable on either C-5 Galaxy aircraft or other cargo ships. The system allows pilots to train and rehearse through networked simulation in a collective and combined arms simulated battlefield environment.

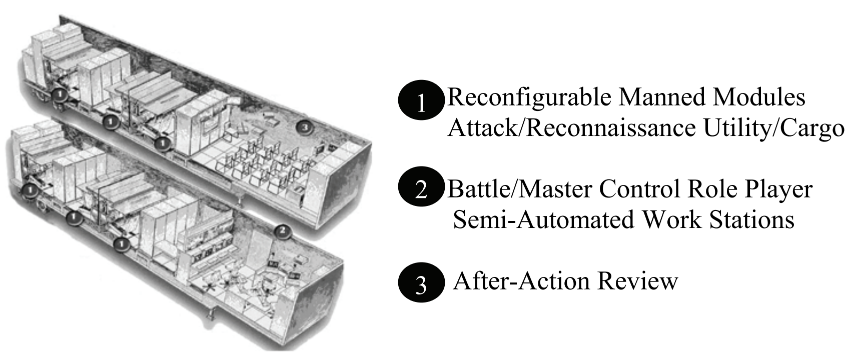


Figure 3-33. AVCATT-A Trailers (Kauchak, 2001).

Each AVCATT-A unit includes 12 HMD systems, the Rockwell Collins' model SimEye XL 100A (Figure 3-34). The SimEye features a full-color SXGA resolution (1280 x 1024) display and presents a 100° (H) x 50° (V) FOV (Rockwell Collins, 2006).

Figure 3-34. SimEye XL 100A (Rockwell Collins).

Major technical performances parameters include:

- Configuration: Binocular, see-through, color
- See-through transmission: > 20%
- Luminance: 1-20 fL (peak white)
- FOV: 100° x 50°, with 30° Overlap
- Resolution: XGA, (1024 x 768)
- Eye relief: >25 mm (Eyeglasses compatible)
- Exit pupil: 15mm
- Mass: 2.5 kg (5.5 lbs) including helmet, optics and displays

Flight School XXI (United States)

A second example of HMD application to simulation and training is in the U.S. Army's Flight School XXI (FSXXI) program. FSXXI is being implemented in the Aviation Warfighter Simulation Center situated at the U.S. Aviation War Fighting Center at Fort Rucker, AL. The primary FSXXI objective is to ensure that the aviators who leave the Fort Rucker, AL, training facility have the necessary experience in their aircraft prior to undertaking combat missions. All future army aviators will be trained under the FSXXI program.

Flight School XXI uses of three types of simulators: the Operational Flight Trainer (OFT), which is the highest fidelity training device that has a wide visual display and is motion-based; the Instrument Flight Trainer (IFT) (Figure 3-35, Top), which is essentially the same as an OFT except it is not on a motion platform and has a smaller visual presentation; and Reconfigurable Collective Training Devices (RCTDs), which enable collective training and can be reconfigured to simulate the Army's UH-60A/L, CH-47D, OH-58D, AH-64A and AH-64D aircraft (Chisholm, 2006). Integral to the IFT cockpits are HMD systems (Figure 3-35, Bottom). Currently, the HMD employed is the Advanced Helmet Mounted Display (AHMD) developed by Link Simulation and Training, Arlington, TX (an L-3 Communication company).

Figure 3-35. Flight School XXI simulator (Top) and Advanced Helmet-Mounted Display (Bottom) (Sisodia et al., 2007).

Major technical performances parameters of the AHMD include:

- Configuration: Binocular, see-through, color
- See-through transmission: > 60%
- Luminance: 0.02-22 fL (peak white)
- FOV: 100° x 50°, with 30° overlap
- Resolution: SXGA, (1280 x 1024)
- Eye relief: > 60 mm
- Exit pupil: 15mm

Medical platform

Advanced Flat Panel (AFP) (United States)

The medical community has developed a broad range of procedures and methodologies that require use of high resolution color video technology. The Advanced Flat Panel (AFP) program's goal (Girolamo, 1997) was to develop color VGA and SXGA and monochrome UXGA (2560 x 1280 pixels) stereoscopic HMDs for arthroscopic and endoscopic surgical applications that meets the comfort and performance requirements for an operating room environment – including the need for sterilization. Two major applications were identified: medical surgery and diagnostic systems that use color video borescopes and portable information display systems that use high resolution computer graphics and the AFP program was initiated by DARPA in June 1994. The AFP design focused on three critical aspects of the system (Nelson and Helgeson, 1996):

- High quality color imagery comparable to that available via 21" CRT monitors used in the operation room
- Exceptional user comfort – both mechanical and visual – so as to not increase surgeon's physical burden or stress while using the HMD
- System compatibility with the operating room, including other user-worn equipment and cleaning requirements.

U. S. Army surgeons from the Madigan Army Medical Center (Tacoma, WA) and the U. S. Army 47th Combat Support Hospital performed 15 arthroscopic knee surgeries, including the first ever arthroscopic surgeries I a field-deployed Combat Support Hospital using the system (Nelson et al., 1997). It was generally agreed that the HMD provides additional benefits for the combat medical community in warfighting environment.

One of the most difficult requirements for medical HMD systems is the color gamut and rendition quality, as surgeons relay heavily on color and color discrimination. This is further complicated by the criticality of the shades of gray accuracy to monitor subtle color changes, particularly in red and blue. The flat panel technology at the time had difficulties meeting these requirements, an Operational Requirement Document was never generated and the program terminated in 1997

User Acceptance

Every day, the "next great idea" ends up as a failure in the eyes of the consumer. Unless the need (real, induced or imagined) for a product is paramount to the task at hand or to health and safety (and that does not always win out), user acceptance usually is the more overriding factor.

From their first conception, HMDs have had to overcome their disadvantages of increased head-supported weight and center-of-mass offsets being the most difficult. These and other inherent HMD characteristics impact comfort, which is a major factor in user acceptance.

However, physical discomfort associated with HMDs may be of lesser importance when compared to potentially disastrous consequences if sensory, perceptual and cognitive issues associated with the design and use of HMDs are not as equally taken into account and carefully investigated.

This is especially true in military scenarios where the mismatch of HMD sensory inputs to the human senses may result in loss of information transfer at best and loss of situation awareness at worst, a consequence that may result in loss of life and equipment.

References

Ackerman, J. (2002). Application of augmented reality to laparoscopic surgery. Doctorate dissertation submitted to the faculty of The University of North Carolina at Chapel Hill.

BAE Systems. (2007). The Q-Sight™ family of helmet display products. Retrieved March 2, 2008 from: www.baesystems.com/BAEProd/ groups/public/documents/bae_publication/ bae_pdf_eis_q-sight.pdf

Bailey, R., Arthur J., III, Prinzel L., III, and Kramer, L. (2007). Evaluation of head-worn display concepts for commercial aircraft. *Proceedings of SPIE*, 6557, 65570Y-1 to 65570Y-16.

Bajura, M. (1992). Merging virtual objects with the real world: Seeing ultrasound imagery within the patient. Computer Graphics, *Proceedings of SIGGRAPH.*, 26(2), 203-210.

Bayer, M. (January 4, 2007). Personal files.

Beal, C., and Sweetman, B. (1994). Helmet-mounted displays: Are we jumping the gun? *International Defense Review*, September, 69-75.

Beal, C., and Sweetman, B. (1997). A new vision: Helmet-mounted displays take multi-track approach. *Jane International Defense Review*, August, 41-47.

Behar, I., Wiley, R.W., Levine, R.R., Rash, C.E., Walsh, D.J., and Cornum, R.L. (1990). Visual Survey of Apache Aviators (VISAA). Fort Rucker, Alabama: U. S. Army Aeromedical Research Laboratory. USAARL Report 90-15.

Braybrook, R. (1998). Looks can kill. *Armed Forces Journal International*, 4, 44.

Brindle, J.H., Marano-Goyco, J., and Tihansky, P.M. (1995). Helmet-mounted sight/display system (HMS/DS) technology development status/vision. NAWCADWAR Advanced Helmet Vision System Development Program, Report No. 1.

Bull, G.C. (1990). Helmet display options-A Routemap. *Helmet- Mounted Displays II, Proceedings of SPIE*, 1290, 81-92.

Cameron, A.A., and Steward, D.G. (1994). The Viper HMD - from design concept to flight test. *Helmet- and Head-Mounted Displays and Symbology Design Requirements, Proceedings of SPIE*, 2218, 137-148.

Casey, C. (1991). Task training with a Helmet Integrated Display Simulator System. *Proceedings of SPIE*, 1456, 175-178.

Casey, C. (1999). Helmet mounted displays on the modern battlefield. *Helmet- and Head-Mounted Displays IV*, *Proceedings of SPIE*, 3689, 270-277.

Chapman, F.W., and Clarkson, G.N. (1992). The advent of helmet-mounted devices in the combat aircraft cockpit – An operator viewpoint. *Proceedings of SPIE*, 1695, 26-37.

Chisholm, P. (2006). 21st century helicopter training. *Military Training Technology* (Online Edition). 11(1).

Chung, J. (1989). Exploring virtual worlds with HMDs. TR89-009.

Davis, L. (2002). Application of Augmented Reality to Visualizing Anatomical Airways. *Proceedings of SPIE*, 4711, 400-405.

Dornheim, M. (1995). VTAS sight fielded, shelved in the 1970's. *Aviation Week and Space Technology*, October, 23, 51.

Drascic, D., and Milgram, P. (1996). Perceptual issues in augmented reality. *Proceedings of SPIE*, 2653, 123-134.

Duchowski, A. (2000). Binocular Eye Tracking in virtual reality for inspection training. *Proceedings of the Eye Tracking Research and Applications Symposium,* Palm Beach Gardens, FL, November 6-8, 89-96.

Dupont Corporation. (2004). Case Study: Cadillac XLR has new-generation Head-Up Display (HUD). Retrieved from http://www2.dupont.com/Automotive/en_US/applications/caseStudies/case178.html

Elbit Systems. (2004). MiDASH Modular Integrated Display and Sight System for helicopter pilots.

Foyle, D.C., McCann, R.S., Sanford, B.D., and Schwirzke, F.J. (1993). Attentional effects with superimposed symbology: Implications for head-up displays. *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*, Santa Monica, CA, 2, 1350–1354.

Geiselman, E.E. (1994). Utility of off-boresight helmet-mounted symbology during a high angle airborne target acquisition task. *Helmet- and Head-Mounted Displays and Symbology Design Requirements, Proceedings of SPIE*, 2218, 328-338.

Girolamo, H.J. (1997). Advanced Information Displays for the 21st Century Warrior. *Information Display,* 13(3), 10-17.

Gizmag.com. (2006). Trimersion HMD takes first person shooter games to a new level of reality. Retrieved October 31, 2007 from: http://www.gizmag.com/ go/6410/

Haar, R. (2005). Virtual reality in the military: Present and future. Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, the Netherlands.

Hale, S. and Piccione, D. (1989). Pilot assessment of the AH-64 helmet-mounted display system. *Proceedings of the 5th International Symposium on Aviation Psychology*, 1, 307-312.

Harding, T.H., Beasley, H.H., Martin, J.S., Rash, C.E., McLean, W.E., Mora, J.C., and McEntire, B.J. (1998). Optical and biodynamic evaluation of the Helmet Integrated Display Sight System (HIDSS) for the RAH-66

Comanche development and validation program phase. Fort Rucker, Alabama: U. S. Army Aeromedical Research Laboratory. USAARL Report No. 98-22.

Harding, T.H., Martin, J.S., Beasley, H.H., and Rash, C.E. (2004). Evaluation of the Microvision helmet-mounted display technology for synthetic vision application engineering prototype for the Virtual Cockpit Optimization Program. Fort Rucker, Alabama: U. S. Army Aeromedical Research Laboratory. USAARL Report No. 2004-02.

Harris, D., and Muir, H. (Editors). (2005). *Contemporary issues in human factors and aviation Safety*. Burlington, Vermont: Ashgate Publishing.

Hiatt, K.L., Rash, C.E., Harris, E.S., and McGilberry, W.H. (2004). Apache aviator visual experiences with the IHADSS helmet-mounted display in Operation Iraqi Freedom. Fort Rucker, Alabama: U. S. Army Aeromedical Research Laboratory. USAARL Report No. 2004-18.

Heinecke, J.K., Rash, C.E., Ranaudo, R.J., and Hiatt, K.L. (2008). Apache aviator evaluation of dual technology night vision systems in Operation Iraqi Freedom urban combat. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 2007-05.

Hopper, D.G. (2000). Reality and Surreality of 3-D Displays: Holodeck and beyond. Invited Keynote Paper in the *Electronic Information Display Conference,* Society for Information Display ExCel, England U.K., November 21-23, 2000.

Hughes, D. (1994). Off-boresight missile test highlights U.S. Capability. *Aviation Week and Space Technology*, 6, 66-69.

Jennings, S. (1997). An in-flight evaluation of stereoscopic imagery in helicopter cockpits. *SPIE Aerosense*, *Proceedings of SPIE,* 3057, 108-117.

Johnston, R.S. and Willey, S.R. (1995). Development of a commercial retinal scanning display. *Helmet- and Head-Mounted Displays and Symbology Design Requirements II, Proceedings of SPIE,* 2465, 2-13.

Kalich, M.E., Rash, C.E., McLean, W.E., and Ramiccio, J.G. (2007). A limited flight study for investigating hyperstereo vision. *Head- and Helmet-Mounted Displays XII: Design and Applications*. In: Brown, R.W., Reese, C.E., Marasco, P.L., and Harding, T.H. (Eds.), *Proceedings of SPIE,* 6557, 65570I.

Kaiser Electro-Optics, Inc. (2007). *XL Series Head-mounted displays*.

Kauchak, M. (2001). AVCATT-A enters low-rate initial production. *T&S 2001, An Armed Forces Journal Global Publication*, Winter, 56-57.

Keller, K., and Colucci, D. (1998). Perception in HMDs: What is it in head-mounted displays (HMDs) that really make them all so terrible? *Proceedings of SPIE,* 3362, 46–53.

Klass, P.J. (1972). Navy pilots to use helmet sight. *Aviation Week and Space Technology*, January 31, 37-40.

Lucas, T. (1994). Advances in helmet-mounted displays. *Avionics*, June. pp. 20-27.

Manning, S.D. and Rash, C.E. (2007). A moveable view. *AeroSafetyWorld*. Flight Safety Foundation. 2, 41-44.

Marshall, G.F. (1989). Back from the past. helmet-mounted display, *Proceedings of SPIE*, 1116, 2-11.

McCann, R.S., Foyle, D.C., and Johnson, J.C. (1993). Attentional limitations with head-up displays. In: Jenson, R.S. (Ed.), *Proceedings of the 7th International Symposium on Aviation Psychology*. Columbus, Ohio: Ohio State University, 70-75.

McCann, R.S. and Foyle, D.C. (1995). Scene-linked symbology to improve situation awareness. *AGARD Conference Proceedings,* No. 555, Aerospace Medical Panel Conference on Situation Awareness, 16:1-16:11.

McLean, W.E., Rash, C.E., McEntire, J., Braithwaite, M.G., and Mora, J.C. (1998). A performance history of AN/PVS-5 and ANVIS image intensification systems in U.S. Army aviation. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 98-28.

Melzer, J.E., and Larkin, E.W. (1987). An integrated approach to helmet display system design. *Display System Optics, Proceedings of SPIE*, 778, 83-88.

Melzer, J.E., and Moffitt, K. (1997). *Head-Mounted Displays: Designing for the User*. New York: McGraw-Hill.

Merryman, R.K. (1994). Vista Sabre II: Integration of helmet-mounted tracker/ display and high boresight missile seeker into F-15 aircraft". *Proceedings of SPIE*, 2218, 173-184.

Microvision, Inc. (2005). Specification sheet: SPECTRUM SD2500.

Milgram, P. (1994). Augmented reality: A class of displays on the reality-virtuality continuum. *Proceedings of SPIE*, 2351, 282-292.

Moore, J., Dennis, S., Thome, M., and Scalf, W.D. (1999). The use of Simulation and Modeling for Acquisition, Requirements, and Training (Smart) in the Virtual Cockpit Optimization Program (VCOP). The Interservice/Industry Training, Simulation and Education Conference (I/ITSEC).

Nelson, S. (1994). Combat vehicle crew helmet-mounted display: next generation high-resolution head-mounted display. In: Lewandowski, R., Stephens, W., and Haworth, L. (Ed.), *Helmet- and Head-Mounted Displays and Symbology Design Requirements*, *Proceedings SPIE,* 2218, 7-16.

Nelson, A.S., and Helgeson, M. (1996). High resolution color flat panel head-mounted display design for the advanced flat panel program. *Proceedings of SPIE*, 2735, 124-133.

Nelson, S., Jones, C., Pierre, P., and Sampson, J. (1997). Arthrooscopic knee surgery using the advanced flat panel high resolution color head-mounted display. *Proceedings of SPIE*, 3058, 170-177.

Primeau, G. (2000). Wide field-of-view SVGA sequential color HMD for use in anthropometric telepresence application. *Proceedings of SPIE*, 4711, 11-20.

Proctor, P. (1996). Retinal displays portend synthetic vision, HUD advances. *Aviation Week and Space Technology*, 15, 58.

Qt Auto News. (2006). HUD technology keeps your eye on the road. *Auto News*, Retrieved from http://www.qtautonews.com/2006/04/25/hud-technology-keeps-your-eye-on-the-road/

Rash, C.E. (Editor) (2000). *Helmet-mounted displays: Design issues for the rotary-wing environment*. Bellingham, WA: SPIE Press.

Rash, C.E. (2006a). Shutting out the noise. *AviationSafetyWorld,* 1 (November), 42-45.

Rash, C.E. (2006b). Helmet-mounted displays. *Special Operations Technology,* 4(5), 6-8.

Rash, C. E. (2008). A 25-year retrospective review of visual complaints and illusions associated with a monocular helmet-mounted display. *Health and Safety Aspects of Visual Displays*, *Displays*, 29(2), 70-80.

Reinhart, W. (1991). Depth cueing for visual search and positioning. *Proceedings of SPIE*, 1457, 221-232.

Rockwell Collins. (2006). Rockwell Collins Sim-Eye 100. Retrieved February 28, 2008 from ProductsAndServices/VisionSystems/HeadMountedDisplays/SIM-EYE-SR100/SimeEye_SR100_071706.pdf

Rockwell Collins. (2008a). EyeHUD Day/Night helmet-mounted display system. Retrieved February 20, 2008 from http://www.rockwellcollins.com/ecat/gs/EyeHUD.html

Rockwell Collins. (2008b). Retrieved February 10, 2008 from http://www.rockwellcollins.com/products/gov/defense_electronics/ displays1/index.html

Rolland, J. (2002). Head-mounted projective displays for creating distributed collaborative environments. *Proceedings of SPIE*, 4711, 395-399.

Seeman, J., De Maio, J., Justice, S., Wasson, J., Derenski, P., Hunter, M., and Walrath, L. (1992). Advanced helicopter pilotage visual requirements. *Proceedings of the American Helicopter Society*, 48, 233-252.

Shontz, W.D., and Trumm, G.A. (1969). Perceptual processes and current helmet-mounted display concepts. Minneapolis, Minnesota: Honeywell Inc. Technical Note TN-1.

Simons, R., Schaefer, J., and Melzer, J. (2002). Visualization solutions for AVCATT-A reconfigurable cockpits. The Interservice/Industry Training, Simulation and Education Conference (I/ITSEC), Orlando, FL.

Sisodia, A, Riser, A., Bayer, M., and Mcquire, J.P. . (2007). Advanced helmet mounted display (AHMD) for simulator applications. Retrieved from http://www.link.com/pdfs/AHMD_2006_Paper.pdf

SPG Media. (2008). Land Warrior Integrated Modular Fighting System, USA. Retrieved February 28, 2008 from http://www.army-technology.com/projects/land_warrior/

Sutherland, I.V. (1965). The ultimate display. *Proceeding of the IFIP Congress*, 2, 506-508.

Vora, J. (2002). Using virtual reality technology for aircraft visual inspection training: presence and comparison studies. *Applied Ergonomics*, 33, 559–570.

Vos, G. D., and Brandt, G. (1990). Use of holographic optical elements in HMDs. *Helmet Mounted Displays II, Proceedings of SPIE*, 1290, 70-80.

White, J., and Cameron, A. (2001). Knighthelm 24-hour HMD. *Helmet Mounted Displays VI, Proceedings of SPIE*, 4361, 164-175.

Wickens, C.D., and Long, J.L. (1994). Conformal symbology, attention shifts, and the head-up display. *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, Human Factors and Ergonomics Society. Santa Monica, California: Human Factors Society, 2, 1350–1354.

Wood, R. B. (1992). Holographic head-up displays. *Electro-optical displays*, In: Karim, M. (Ed.). New York: Marcel Dekker. 337-415.

Yona, Z., Weiser, B., and Hamburger, O. (2004). Day/night ANVIS/HUD-24 (Day HUD) flight test and pilot evaluations. *Helmet- and Head-Mounted Displays IX: Technologies and Applications*. In: Rash, C.E., and Reese, C.E., (Editors), *Proceedings of the SPIE*, 5442, 225-235.

Zintsmaster, L.R. (1994). Wide-Eye™ helmet mounted display system for rotorcraft applications. *IEEE Aerospace and Electronic Systems Magazine*. 9(3), 6-11.