5

Head-Mounted Displays

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5.1 Introduction

Head-Mounted Displays (HMD)* are personal information-viewing devices that can provide information in a way that no other display can. While they can be used as hands-off information sources, the displayed video can also be made reactive to head and body movements, replicating the way we view, navigate through, and explore the world. This unique capability lends itself to applications such as Virtual Reality for creating artificial environments,[1] to medical visualization as an aid in surgical procedures,[2,3] to military vehicles for viewing sensor imagery,[4] to airborne workstation applications reducing size, weight, and power over conventional displays,[5] to aircraft simulation and training,[6–8] and (central to this chapter) for fixed and rotary wing avionics display applications.[9,10]

In some applications, such as the medical and soldier's displays in Figure 5.1, the HMD is used solely as a hands-off information source. To truly reap the benefits of the HMD as part of an avionics application, however, it must be part of a Visually Coupled System (or VCS) that includes the HMD, a head position tracker, and a graphics engine or video source.[11,12] As the pilot turns his/her head, the tracker relays the orientation data to the mission computer, which updates the displayed information accordingly. This gives the pilot a myriad of real-time data that is *linked to head orientation.* In a fixed-wing fighter, a missile's sensor can be slaved to the pilot's head line-of-sight, allowing the pilot to designate targets away from the forward line-of-sight of the aircraft. In a helicopter, the pilot can point sensors such as forward-looking infrared (FLIR)** and fly at night.

The U.S. military introduced HMDs into fixed-wing aircraft in the early 1970s for targeting air-to-air missiles. Several hundred of the Visual Targeting Acquisition Systems (VTAS) were fielded on F-4 Phantom fighter jets between 1973 and 1979.[10,13] This program was eventually abandoned because the HMD

*The term Head-Mounted Display is used in this chapter as a more generic term than Helmet-Mounted Display which more often refers to military-oriented hardware. Helmet-Mounted Sight (HMS) is another term often used referring to an HMD that provides only a simple targeting reticle.

**Forward-Looking Infrared (FLIR) is a sensor technology that creates shades-of-grey imagery of objects from slight differences in black-body thermal emissions.

FIGURE 5.1 Three different applications for HMDs: the CardioView® for minimally invasive cardiac surgery (photo courtesy of Vista Medical Technologies, Inc.), a prototype of the U.S. Army Land Warrior HMD (photo courtesy of Program Manager, Soldier, U.S. Army), and the SIM EYE XL100 for aviation training (photo courtesy of Kaiser Electro-Optics).

capabilities were not matched by missile technology of the day.* HMDs were given new life when a Soviet MiG-29 was photographed in 1985 showing a simple helmet-mounted sight for off-axis targeting of the Vympel R-73 missile — also called the AA-11 Archer. With this revelation, the Israelis initiated a fast-paced program that deployed the Elbit DASH HMD for off-axis targeting of the Rafael Python 4 missile in 1993-94.[14]

Two doestic studies — Vista Sabre[15] and Vista Sabre II[16] — demonstrated the clear advantages for a pilot equipped with an HMD for missile targeting over one using only his HUD. Encouraged by these and by a post-Berlin Wall examination of the close-combat capabilities of the HMD-equipped MiG-29,[17] the U.S. military initiated their own off-boresight missile targeting program. The result is the Joint Helmet Mounted Cueing System (JHMCS, built by Vision Systems International) scheduled to deploy on the U.S. Navy F/A-18, the U.S. Air Force F-15 and F-22, and on both domestic and international versions of the F-16 early in the 21st century. The JHMCS will give pilots off-axis targeting symbology for the AIM-9X missile, aircraft status,[18] and provide them with improved situational awareness of the airspace surrounding the aircraft.

The U.S. Army has taken a more aggressive approach with HMD technology, putting it on rotary wing aircraft starting with the AH-1S Cobra helicopter gunship in the 1970s. A turreted machine gun is slaved to the pilot's head orientation via a mechanical linkage attached to his helmet. The pilot aims the weapon by superimposing a small helmet-mounted reticle on the target.[19]

In the 1980s, the Army adopted the Integrated Helmet and Sighting System (IHADSS) for the AH-64 Apache helicopter. This monocular helmet-mounted display gives the pilot the ability — similar to the Cobra gunship — to target head-slaved weapons. The IHADSS has the added ability to display head-tracked FLIR imagery for nighttime flying. Over 5000 of these CRT-based, monochrome systems have been delivered by Honeywell on this very successful program for the Army.[10]

Using an HMD as a key interface to the aircraft has proven so effective that the Army's newest helicopter, the RAH-66 Comanche will field the binocular Helmet Integrated Display Sighting System (HIDSS) when it is deployed early in the 21st century.

In addition to these domestic applications, HMD-based pilotage systems are being adopted throughout the international aviation community on platforms such as Eurocopter's Tiger helicopter scheduled for deployment early in the 21st century. The U.S. Army also has extensive experience using helmet-mounted Night Vision Goggles (NVGs) in aviation environments. These devices have their own unique set of performance, interface, and visual issues [20–23] and are discussed in more detail elsewhere in this book.

*There was also a Memorandum of Understanding signed in 1980 that relegated the development of short-range missile technology (and therefore HMDs) to the Europeans.

FIGURE 5.2 The U.S. Air Force and Navy's Joint Helmet Mounted Cueing System helmet-mounted display that will go into service early in the 21st century. (Photo courtesy of Vision Systems International, used with permission.)

FIGURE 5.3 The Honeywell IHADSS is a monocular, monochrome, CRT-based, head-tracked, see-through helmet-mounted display used on the U.S. Army AH-64 Apache helicopter. (Photo courtesy of Honeywell Electronics, used with permission.)

5.2 What Is an HMD?

In its simplest incarnation, an HMD consists of one or more image sources, collimating optics, and a means to mount the assembly on the head. In the IHADSS HMD shown in Figure 5.3, the image source is a single, high-brightness cathode ray tube (CRT). The monocular optics create and relay a virtual image of the CRT surface, projecting the imagery onto the see-through combiner to the pilot's eye. This display module is attached to the right side of the aviator's protective helmet with adjustments that let the pilot position the display to see the entire image.

The early VTAS and Cobra helicopter HMDs used a simple targeting reticle to point weapons similar to the one shown on the left in Figure 5.5. The JHMCS HMD has a more sophisticated targeting capability including "look-to" and shoot cues (similar to the one shown on the right side of the same figure), as well as altitude, airspeed, compass heading, and artificial horizon data. With the IHADSS, the AH-64 Apache helicopter pilot sees a similar symbology set augmented with head-tracked FLIR data.

FIGURE 5.4 A prototype of the Kaiser Electronics' HIDSS for the RAH-66 Comanche helicopter. (Photo courtesy of Kaiser Electronics, used with permission.)

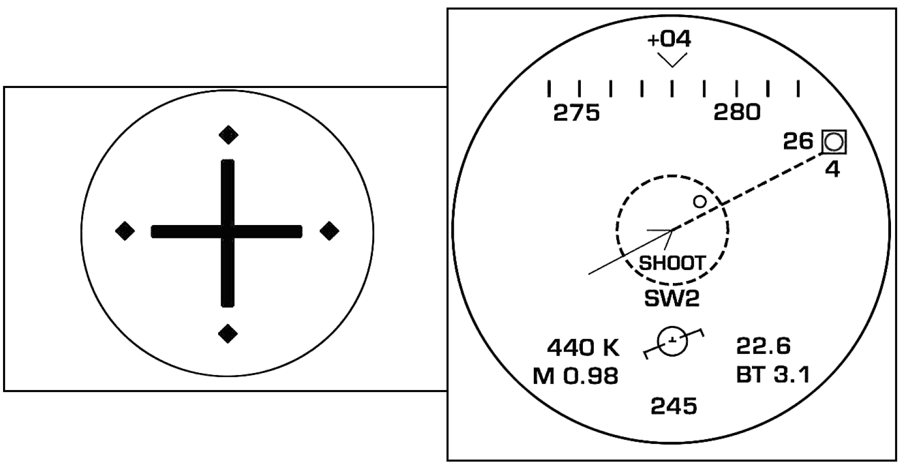


FIGURE 5.5 Comparison of early HMD reticle imagery (left) with a more capable symbology set (right) to be used with the HMDs such as the JHMCS.

This collection of components, though deceptively simple, has at its core a complex interaction of system and hardware issues as well as visual, anthropometric, physical, and display issues. These in turn are viewed by an equally complex *human perceptual system*.[24] The design task is complicated further in the aircraft environment, because the HMD — now a *helmet*-mounted display — provides both display and life support for the pilot. Issues of luminance, contrast, alignment, and focus must be addressed while not impacting pilotage or crash safety. For all these reasons, HMD design requires a careful balancing — a *suboptimization* — of both display and physical requirements.

The next sections will examine the important components or features in an HMD.

5.2.1 Image Sources for HMDs

As of the year 2000, almost all of the HMDs deployed use CRTs as image sources, primarily because the technology is the most mature. It can provide the required high luminance and the HMDs can be ruggedized to withstand the harsh military environment.[25] Over the last decade, however, small, flat-panel image sources have improved to where they are being considered as alternatives to CRTs because of their reduced size, weight, and power requirements. [26,27]

There are two major categories of image sources, *emissive* and *nonemissive* (see Table 5.1). The *non-emissive image sources* modulate a separate illumination on a pixel-by-pixel basis to create the desired imagery. Examples are

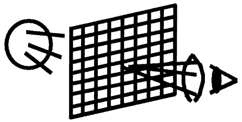
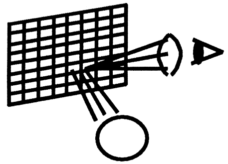
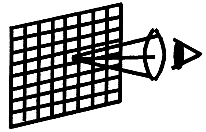
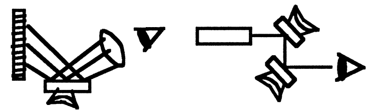
- *Transmissive Liquid Crystal Displays (LCD)* — The pixel matrix is illuminated from the rear. A modulated electric field controls the transmission of the backlight through the individual liquid crystal-filled cells. Quality transmissive LCDs are manufactured in large quantity in Japan, though in limited quantity domestically.
- *Reflective Liquid Crystal on Silicon Displays (LCOS)* — This is the same as the transmissive device except that the image source is illuminated from the front. The light transmits through the cell and reflects off a mirror-like surface when the pixel is transmitting and is scattered when the pixel is turned off. This is a fast-growing area of development in the U.S. because the manufacturing technology is similar to silicon wafer fabrication.
- *Scanning Display* — A point source (such as a laser) or line of point sources (such as LEDs) is modulated in one or more directions using resonance scanners or opto-acoustic modulators to produce imagery. One example is the Retinal Scanning Display (RSD).[28,29]

Emissive devices represent a large category of image sources in which the image plane of the device emits light without the need for supplemental illumination. Such devices include:

- *Active Matrix Electroluminescent (AMEL)* — A thin-film layer of luminescent phosphor is sandwiched between two electrodes, one transparent, in a pixilated array. The pixels are digitally addressed using high-frequency pulses to achieve grayscale. Recent improvements use a quasi-analog addressing to achieve greater grayscale range and improved luminance. These are compact and very rugged devices.[30]
- *Cathode Ray Tube (CRT)* — This is a vacuum tube with an electron gun at one end and a phosphor screen at the other. A beam from the electron gun is modulated by deflection grids and directed onto the screen. The incident electrons excite the phosphor, emitting visible light.[25] CRTs can be very bright and very rugged for the aviation environment, though they are larger than flat-panel displays and require high voltage.
- *Vacuum Fluorescent Display (VFD)* — Most commonly seen in alphanumeric displays, the VFD uses a vacuum package containing phosphors that are excited by a series of filaments. These capabilities are being expanded as imaging devices. Though currently available only in low-resolution devices, VFDs may in time become more prevalent.[31]
- *Organic Light Emitting Diodes (OLED)* — A low-voltage drive across a thin layer of organic material causes it to emit visible light when the charge carriers recombine within the material. A very promising technology, though as of this writing it is still in the developmental stages.

The choice of an image source for an HMD is not easy. Depending on the application, it may be preferable to have a backlit (i.e., transmissive) LCD over a reflective one for size, power, or packaging reasons. Or, it may be preferable to have a self-emissive device such as an AMEL with its minimum package size. Another consideration is that liquid crystal-based image sources have a finite area over which the image is observable. Collimating optics with a very short focal length may lose part of the image. When considering which image source to use, designers must be concerned with numerous

TABLE 5.1 Categories of Miniature Image Sources Suitable for HMDs

Technology	Transmissive 	Reflective 	Self-emissive 	Scanning 
Description	Light source illuminates the display from the rear. Pixels are turned on/off or partially on for gray scale. Transistors along the sides of the pixels.	Light source illuminates the front of the display with a reflective surface under each pixel. Pixels are turned on off or partially on for gray scale, blanking out the incident light. Transistors underneath the pixels.	Individual pixels are turned on/off or partially on for gray scale. Transistors underneath the pixels (AMELs, OLEDs). Drive electronics are remote from the image source (CRTs).	Image source (LED or laser) scans across the image plane. Drive electronics are remote from image source surface.
Examples	Active Matrix Liquid Crystal Display (AMLCD)	Reflective Liquid Crystal on Silicon (LCOS) Digital Micromirror Display (DMD)	Active Matrix Electroluminescent (AMEL) Cathode Ray Tube (CRT) Vacuum Fluorescent Display (VFD) Organic Light Emitting Diode (OLED)	Retinal Scanning Display (RSD) Scanning Light-Emitting Diode
Advantages	Very simple illumination design High quality imagery Available commercially in quantity	High luminous efficiency High fill factor (transistors under the pixel)	Smallest package Lightest weight High fill factor (transistors under the pixel) Wide temperature range (AMEL)	High luminance Saturated colors Potential for image plane distortion (RSD)
Disadvantages	Less efficient fill factor Transmission loss through LCD Requires spatial or temporal integration for color (Post) Limited temperature range (LCD) Slower response time (LCD)	Front illumination is more difficult to package Scattered light management is very important Temporal integration for color	Limited luminance Color by temporal integration	Limited availability (RSD) Limited resolution (LED) Packaging limitations

issues such as:

- *Size* — What is the size of the image source itself? If a supplemental illumination source is required, how large is it? How large is the active area of the display? What is the size of the required drive electronics?
- *Weight* — What is the weight of the image source and any required supplemental illumination? If electronic components must be within close proximity to the image source (i.e., head-mounted), how much do they weigh? Can they be taken off the head or moved to a more favorable location on the head? (See Section 5.2.3).
- *Power* — Some image source technologies such as CRTs and AMELs require a high voltage drive. Image sources such as some LCDs have low transmission, requiring a brighter backlight to meet the display luminance requirements.
- *Resolution* — How many pixels can be displayed? Is the image generator or sensor video compatible with this resolution? Is the response time of the image source fast enough to meet pilotage performance requirements?[32] If not, can measures be taken to improve the response time? [33,34]
- *Addressability* — CRTs are considered infinitely addressable because the imagery is drawn in calligraphic fashion. Pixilated devices such as LCDs, AMELs, and OLEDs are considered finite addressable displays because the pixel location is fixed. This limits their ability to compensate for image plane distortion.
- *Aspect ratio* — Most miniature CRTs have a circular format, while most of the solid-state pixilated devices such as LCDs and AMELs have a rectangular format. Flat-panel devices with VGA, SVGA, or XGA resolution have a 4:3 horizontal-to-vertical aspect ratio. SXGA resolution devices have a 5:4 aspect ratio.* This is an important consideration when choosing an image source because it determines the field of view of the display.
- *Luminance and contrast* — It is important that the image source be capable of providing a display luminance that is compatible with viewing against bright ambient backgrounds typically found in aviation environment. (See Section 5.4.3)
- *Color* — Is the image source capable of producing color imagery?[35] Because of the advantage that data color-coding provides to the pilot,[36] color is becoming more prevalent in head-down displays. Though not in widespread use in head-up and head-mounted displays, it may become more important because there are some preliminary indications that high *g*-forces can alter color perception in the cockpit.[37]

As of this writing, most cockpit displays — head-up, head-down, and helmet-mounted — are still CRT-based, though there is movement towards backlit LCDs and some new projection approaches. The Microvision RSD is showing promise because of its potential for a very high luminance output, though still a bit bulky and with limited availability for some HMD applications. It is likely that the first deployed use of a flat-panel image source in an HMD will be for the Comanche HIDSS, using a small, high resolution AMLCD from Kopin.[34]

5.2.2 Optical Design

The purpose of the optics in an HMD is threefold:

- Collimate the image source — creating a *virtual image*, which appears to be farther away than just a few inches from the face.
- Magnify the image source — making the imagery appear larger than the actual size of the image source.
- Relay the image source — creating the virtual image away from the image source, away from the front of the face.

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* VGA is 640 horizontal pixels by 480 vertical rows. SVGA is 800 horizontal pixels by 600 vertical rows. XGA is 1024 horizontal pixels by 768 vertical rows. SXGA is 1280 horizontal pixels by 1024 vertical rows.

There are two optical design approaches common in HMDs. The first is the *non-pupil-forming design* — a simple magnifying lens — hence the term *simple magnifier.*[38,39] It is the easiest to design, the least expensive to fabricate, the lightest and the smallest, though it does suffer from a short throw distance between the image source and the virtual image, putting the whole assembly on the front of the head, close to the eyes. This approach is typically used for simple viewing applications such as the medical HMD (Figure 5.1a) and the Land Warrior display (Figure 5.1b).

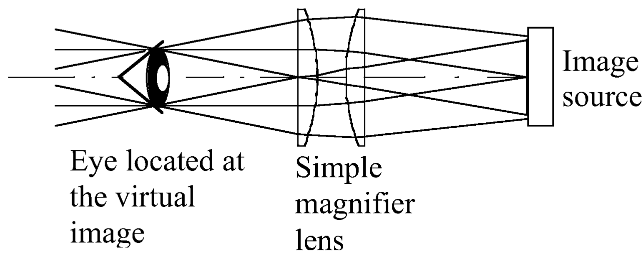


FIGURE 5.6 Diagram of a simple magnifier, or non-pupil-forming lens.

The second optical approach is a bit more complex, the *pupil-forming design.* This is more like the *compound microscope,* or a submarine periscope in which a first set of lenses creates an intermediate image of the image source. This intermediate image is *relayed* by another set of lenses to where it creates a pupil, or a hard image of the intermediate image.

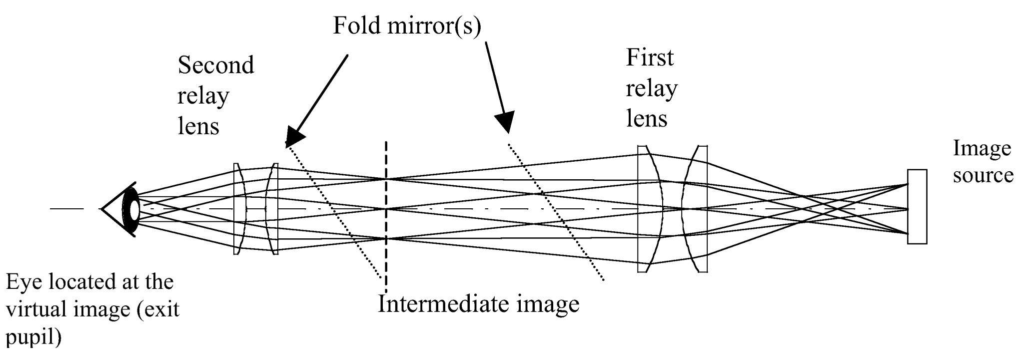


FIGURE 5.7 A pupil-forming optical design is similar to a compound microscope, binoculars, or a periscope.

The advantage is that the pupil-forming design provides more path length from the image plane to the eye. This gives the designer more freedom to insert mirrors as required to fold the optical train away from the face to a more advantageous weight and center of gravity location. The disadvantages are that the additional lenses increase the weight and cost of the HMD and that outside the exit pupil—the image of the stop — there is no imagery. This approach is typically used when the image source is large (such as a CRT) or where it is desirable to move the weight away from the front of the face such as in Figure 5.1c and Figure 5.3.

In each case, the optical design must be capable of collimating, magnifying, and relaying the image with sufficiently small amounts of residual aberrations,[39] with manual focus (if required), and with proper alignment (if a binocular system). In addition, the optical design must provide a sufficiently large exit

TABLE 5.2 Some of the Advantages and Disadvantages of Pupil-Forming and Non-Pupil-Forming Optical Designs for HMDs

	Non-pupil-forming (simple magnifier)	Pupil-forming (relayed lens design)
Advantages	Simplest optical design Fewer lenses and lighter weight Doesn't "wipe" imagery outside of eye box Less eyebox fit problems Mechanically the simplest and least expensive	Longer path length means more packaging freedom. Can move away from front of face. More lenses provide better optical correction
Disadvantages	Short path-length puts the entire display near the eyes/face Short path-length means less packaging design freedom	More complicated optical design More lenses mean heavier design Loss of imagery outside of pupil Needs precision fitting, more and finer adjustments

pupil* so the user doesn't lose the image if the HMD shifts on the head, as well as providing at least 25 mm of eye relief** to allow the user to wear eyeglasses

5.2.3 Head Mounting

It is difficult to put a precise metric on the fit or comfort of an HMD, though it is always immediately evident to the wearer. Even if the HMD image quality is excellent, the user will reject it if it doesn't fit well. Fitting and sizing are especially critical in the case of a helmet-mounted display where, in addition to being comfortable, it must provide a *precision* fit for the display relative to the pilot's eyes.

We can list the most important issues for achieving a good fit with an HMD:

- The user must be able to adjust the display to see the imagery.
- The HMD must be comfortable for long duration wear without causing "hot spots."
- The HMD must not slip with sweating or under *g*-loading, vibration, or buffeting.
- The HMD must be retained during crash or ejection.
- The weight of the head-borne equipment must be minimized.
- The mass-moment-of-inertia must be minimized.
- The mass of the head-borne components should be distributed to keep the center of gravity close to that of the head alone.

The human head weighs approximately 9 to 10 lb and sits atop the spinal column. The Occipital Condyles on the base of the skull mate to the Superior Articular Facets of the first cervical vertebra, the Atlas.[40] These two small, oblong mating surfaces on either side of the spinal column are the pivot points for the head.

The center of gravity (CG) of the head is located at or about the tragion notch, the small cartilaginous flap in front of the ear. Because this is *up* and *forward* of the head/vertebra pivot point, there is a tendency for the head to tip downwards, were it not for the strong counter force exerted by the muscles running down the back of the neck — hence, when people fall asleep they "nod off." Adding mass to the head in the form of an HMD can move the CG (now HMD + head) away from this ideal location. High vibration or buffeting, ejection, parachute opening, or crash will greatly exacerbate the effect of this extra weight and

*The exit pupil is found only in pupil-forming designs such as the SIM EYE (Figure 5.1c), the IHADSS (Figure 5.3), and the HIDSS (Figure 5.4). In non-pupil-forming designs of Figures 5.1a and 5.1b, it is more nearly correct to refer to a *viewing eyebox*, because there is a finite unvignetted viewing area.

**There are some differences in terminology usually relating to the writing of specifications. In the classical optical design, the eye relief is the distance along the optical axis from the last optical surface to the exit pupil. In an HMD with angled combiners, eye relief should be measured from the eye to the closest point of the combiner, whether it is on the optical axis or not.

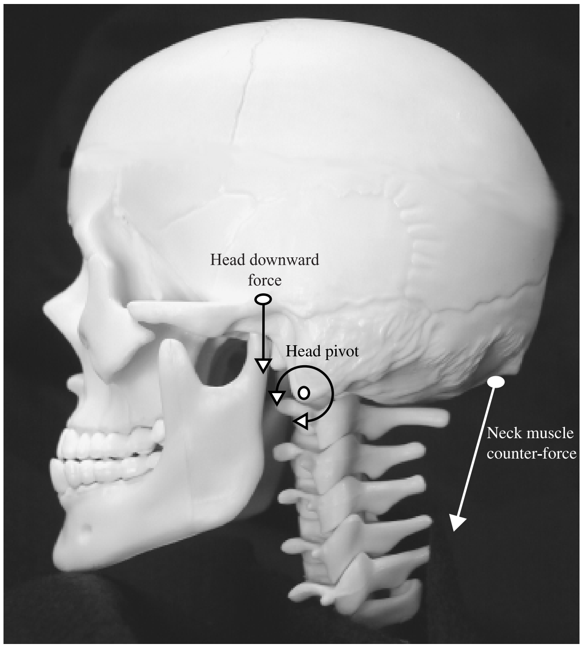


FIGURE 5.8 The human head and neck with the center of gravity located near the tragion notch and the pivot point located at the Occipital Condyles.

displaced CG, with effects that can range from fatigue and neck strain to serious or mortal injury.[41] Designers can mitigate the impact of the added head-borne hardware by first minimizing the mass of the HMD, followed by an optimization of the *location* of the mass to restore the head + HMD CG location to that of the head alone.

This is supported by the extensive biomechanics research at the U.S. Army's Aeromedical Research Labs. Figure 5.9 gives a weight vs. CG curve in the vertical direction, where the area under the curve is considered crash safe for a helicopter environment. The second graph (Figure 5.10) defines the weight/CG combination that will minimize fatigue.[12] Similar work in fixed-wing biomechanics at the Air Force's Wright-Patterson Labs has concluded that the weight of the HMD and oxygen mask cannot exceed 4 lb, and that the resulting center of gravity must also be within a specified region centered about tragion notch.[40]

Anthropometry — "the measure of Man" — is a compilation of data that define such things as the range of height for males and females, the size of our heads, and how far our eyes are apart. Used judiciously, these data can help the HMD designer achieve a proper fit, though an overreliance can be equally problematical. One of the most common mistakes made by designers is to assume a correlation between various anthropometric measurements, because almost all sizing data are *univariate* — that is, they are completely uncorrelated with other data. For example, a person who has a 95th percentile head circumference will not necessarily have a 95th percentile interpupillary distance.[42] One bivariate study did correlate head length and head breadth for male and female aviators, resulting in a rather large spread of data.[43]

There are examples where helmet and HMD developments have been less than successful as a result of an overemphasis on anthropometric data and an underemphasis on fitting, resulting in HMDs that don't fit properly (INIGHTS) or in extraneous helmet sizes (the HGU-53/P).[42]

5.3 The HMD as Part of the Visually Coupled System

In an avionics application, the HMD — be it a Helmet-Mounted Display or Helmet-Mounted Sight — is part of a Visually Coupled System (VCS) consisting of the HMD, a head tracker, and mission computer. As the pilot turns his head, the new orientation is communicated to the mission computer that updates the imagery as required. The information is always with the pilot, always ready for viewing.

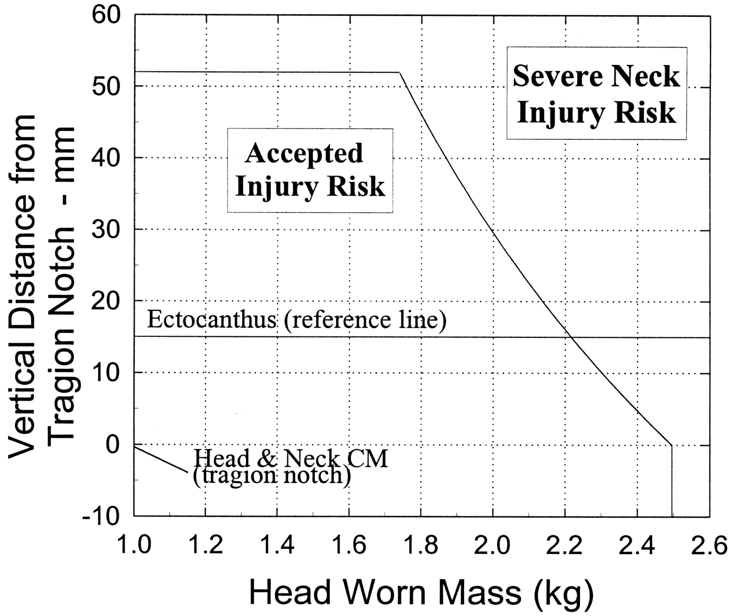


FIGURE 5.9 The USAARL weight and vertical center of gravity curve. The area under the curve is considered crash safe in helicopter environments. (Data curve courtesy of U.S. Army Aeromedical Research Labs, used with permission.)

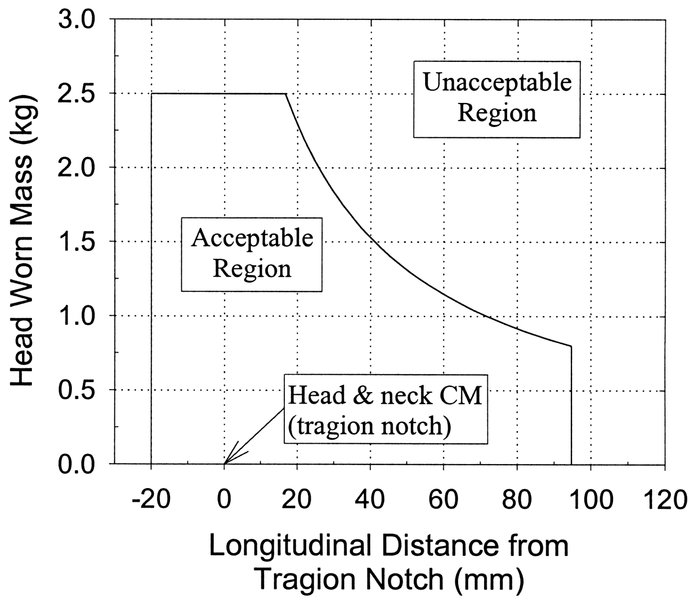


FIGURE 5.10 The USAARL weight and horizontal center of gravity curve with the area under the curve considered acceptable for fatigue in helicopter environments. (Data curve courtesy of U.S. Army Aeromedical Research Labs, used with permission.)

TABLE 5.3 The Univariate (Uncorrelated) Anthropometric Data for Key Head Features. Note the Range of Sizes for the 5th Percentile Female up to the 95th Percentile Male.[44]

Critical Head Dimensions (cm)	5% Female	95% Male
Interpupillary distance (IPD)	5.66	7.10
Head length [a]	17.63	20.85
Head width	13.66	16.08
Head circumference	52.25	59.35
Head height (ectocanthus to top of head)[a]	10.21	12.77

[a] These data are head orientation-dependent.

Early cockpit-mounted displays — Head-Down Displays — gave the pilot information on aircraft status, but required him to return his attention continuously to the interior of the cockpit. This reduced the time he could spend looking outside the aircraft. As jets got faster and the allowable reaction time for pilots got shorter, Head-Up Displays (HUD) provided the next improvement by creating a collimated, virtual image that is projected onto a combining glass located on top of the cockpit panel, in the pilot's forward line of sight.* This means the pilot does not have to redirect his attention away from the critical forward airspace or refocus his eyes to see the image. Because the imagery is collimated — it appears as though from some distant point — it can be superimposed on a distant object. This gives the pilot access to real-time geo- or aircraft-stabilized information such as compass headings, artificial horizons, or sensor imagery.

The HMD expands on this capability by placing the information in front of the pilot's eyes at all times and by linking the information to the pilot's line of sight. While the HUD provides information about only the relatively small forward-looking area of the aircraft, the HMD with head tracker can provide information over the pilot's entire field of regard, all around the aircraft with eyes- and head-out viewing. This ability to link the displayed information with the pilot's line of sight increases the area of regard over which the critical aircraft information is available. This new capability can:

- Cue the pilot's attention by providing a pointing reticle to where a sensor has located an object of interest.
- Allow the pilot to slew sensors such as FLIR for flying at night or in adverse conditions.
- Allow the pilot to aim weapons at targets that are off-boresight from the line of sight of the aircraft.
- Allow the pilot to hand-off or receive target information (or location) from a remote platform, wingman, or other crew member.
- Provide the pilot with aircraft- or geo-stabilized information.

And, in general, provide situational awareness to the pilot by giving him information about the entire space surrounding the aircraft.

One excellent example is the U.S. Army AH-64 Apache helicopter equipped with Honeywell's Integrated Helmet And Display Sighting System (IHADSS) HMD and head tracker. As the pilot moves his head in azimuth or elevation, the tracker communicates the head orientation to the servo system controlling the Pilot Night Vision System (PNVS) FLIR. The sensor follows his head movements, providing the pilot with a viewpoint as though his head were located on the nose of the aircraft. This gives the pilot the ability to "see" at night or in low light in a very intuitive and hands-off manner, similar to the way he would fly during daytime with the overlay of key flight data such as heading, altitude, and airspeed.

Studies are being conducted to find ways to squeeze even more out of the HMD in high-performance aircraft. A recent simulator study at the Naval Weapons Center used the HMD to provide "pathway in the sky" imagery to help pilots avoid threats and adverse weather.[45] Another experimental feature compensated for the loss of color and peripheral vision that accompanies *g*-induced loss of consciousness

*Head-Up Displays are discussed in Chapter 4.

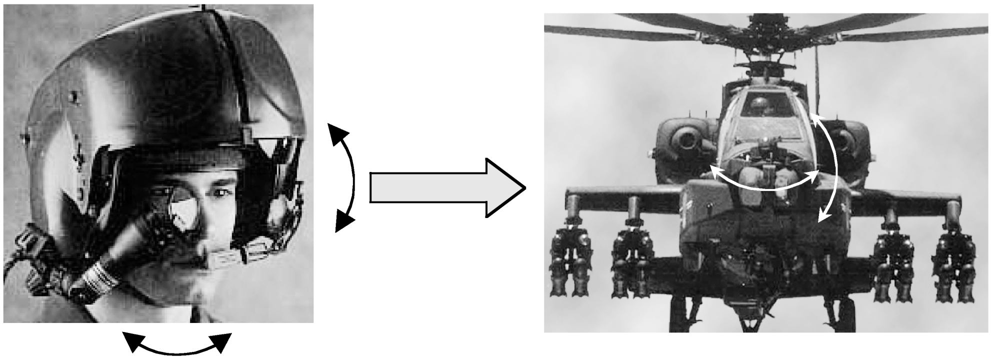


FIGURE 5.11 The linkage between the IHADSS helmet-mounted display and the Pilot's Night Vision System in the AH-64 Apache helicopter. The PNVS is slaved to the pilot's head line of sight. As he turns his head, the PNVS turns to point in the same direction.

(*g*-loc). As the pilot began to "gray-out" the symbol set was reduced down to just a few critical items, positioned closer to the pilot's central area of vision. Another study provided helicopter pilots with earth-referenced navigation waypoints overlayed on terrain and battlefield engagement areas.[46] The results showed significant improvements in navigation, landing, the ability to maintain fire sectors, and an overall reduction in pilot workload.

5.4 HMD System Considerations and Trade-Offs

As mentioned in the Introduction, good HMD design relies on a suboptimization of requirements, trading off various performance parameters and requirements. The following sections will address some of these issues.

5.4.1 Ocularity

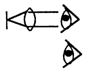
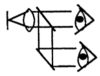
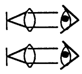
One of the first issues to consider in an HMD is whether it should be monocular, biocular, or binocular,:

Monocular — *a single video channel viewed by a single eye.* This is the lightest, least expensive, and simplest of all three approaches. Because of these advantages, most of the current HMD systems are monocular, such as the Elbit DASH, the Vision Systems International JHMCS (Figure 5.2), and the Honeywell IHADSS (Figure 5.3). Some of the drawbacks are the potential for a laterally asymmetric center of gravity and issues associated with focus, eye dominance, binocular rivalry, and ocular-motor instability.[47,48]

Biocular — *a single video channel viewed by both eyes.* The biocular approach is more complex than the monocular design, though it stimulates both eyes, eliminating the ocular-motor instability issues associated with monocular displays. Viewing imagery with two eyes vs one has been shown to yield improvements in detection as well as providing a more comfortable viewing experience.[49,50] However, since it is now a two-eyed viewing system, the designer is subject to a much more stringent set of alignment, focus, and adjustment requirements. [51] The primary disadvantage of the biocular design is that the image source is usually located in the forehead region, making it more difficult to package. In addition, since the luminance from the single image source is split to both eyes, the brightness is cut in half.

Binocular — *each eye views an independent video channel.* This is the most complex, most expensive, and heaviest of all three options, but one which has all the advantages of a two-eyed system with the added benefit of providing partial binocular overlap (to enlarge the horizontal field of view), stereoscopic imagery, and more packaging design freedom. Examples are the Kaiser Electronics HIDSS (Figure 5.4) and the Kaiser Electro-Optics SIM EYE (Figure 5.1c). A binocular HMD is subject to the same alignment, focus, and adjustment requirements as the biocular design, but the designer can move both the optics and the image sources *symmetrically away* from the face.

TABLE 5.4 Advantages and Disadvantages of Monocular, Biocular, and Binocular HMDs

Configuration		Advantages	Disadvantages
Monocular (1 image source viewed by 1 eye)		Lightest weight Simplest to align Least expensive	Potential for asymmetric center of gravity Potential for ocular-motor instability, eye dominance, and focus issues
Biocular (1 image source viewed by both eyes)		Simple electrical interface Lightweight Inexpensive	More complex alignment than monocular Difficult to package Difficult for see-through
Binocular (2 image sources viewed by both eyes)		Stereo imagery Partial binocular overlap Symmetrical center of gravity	Most difficult to align Heaviest Most expensive

5.4.2 Field of View and Resolution

When asked about HMD requirements, users will typically want more of both field-of-view (FOV) *and* resolution. This is not surprising since the human visual system has a total field of view of 200° horizontal by 130° vertical[52] with a grating acuity of 2 min of arc[53] in the central foveal region, something that HMD designers have yet to replicate. For daytime air-to-air applications in a fixed-wing aircraft, a large FOV is probably not necessary to display the symbology shown in Figure 5.5. If it is a simple sighting reticle, the FOV can be approximately 6°. For an HMD such as the JHMCS system where the pilot will receive aircraft and weapons status information, a 20° FOV is more effective. If the HMD is intended to display sensor imagery for nighttime pilotage such as with the IHADSS (a rectangular 30° by 40° FOV), the pilot will "paint" the sky with the HMD, creating a mental map of his surroundings. The larger FOV is advantageous, because it provides peripheral cues that contribute to the pilot's sense of self-stabilization, and it lowers pilot workload by reducing the range of head movements needed to fill in the mental map.[54–56] Most night vision goggles such as the ANVIS-6 have a field of view of 40° circular, though most pilots would prefer more. The Comanche HIDSS will have a rectangular field of view of 35° by 52°.

While display resolution contributes to overall image quality, there is also a direct relationship with performance. If we examine the Johnson criteria for image recognition, we can see that the amount of resolution required is (like most HMD-related issues) task-dependent. For an object such as a tank, increased resolution will allow the pilot to Detect ("something is there"), Recognize ("it's a tank"), or Identify ("it's a T-72 tank")[57] at a particular distance.

While more of each is desirable, FOV and resolution in an HMD are linked by the relationship:

$$H = F * \operatorname{Tan} \Theta$$

where F is the focal length of the collimating lens. If :

- H is the size of the image source, then Θ *is the field of view*, or the apparent size of the virtual image in space.
- H is the pixel size, then Θ *is the resolution* or apparent size of the pixel in image space.

Thus, the focal length of the collimating lens *simultaneously* governs the field of view (which you want large) *and* the resolution (which you want small). For a display with a single image source, the result is either wide field of view, *or* high resolution, but *not both* at the same time.

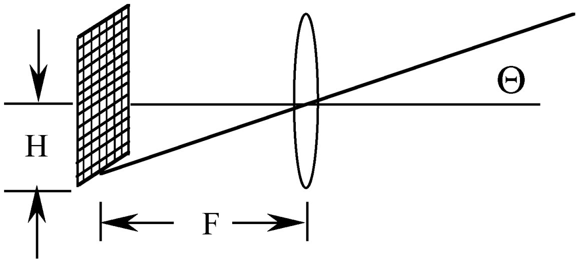


FIGURE 5.12 The focal length of the collimating lens determines the relationship between H, the size of the image source (or pixel size) and Θ, the field of view (or the resolution).

Given this $F * Tan\Theta$ invariant, there are at least four ways to increase the field of view of a display and still maintain resolution. These are (1) high-resolution area of interest, (2) partial binocular overlap, (3) optical tiling, and (4) dichoptic area of interest.[58,59] Of these, partial binocular overlap is preferable for binocular flight applications, though optical tiling is under investigation to expand the field of view of night vision goggles.[60]

FIGURE 5.13 Proview™ 100 HMD mounted on SPH-4B helicopter helmet for a simulator application. This is an example of an optically tiled see-through HMD with 100° by 30° field of view. (Photo courtesy of Kaiser Electro-Optics, used with permission.)

Partial binocular overlap results when the two HMD optical channels are canted either inward (convergent overlap) or outward (divergent overlap). This enlarges the horizontal field of view, while maintaining the same resolution as the individual monocular channels. Partial overlap requires that two image sources and two video channels are available and that the optics and imagery are properly configured to compensate for any residual optical aberrations. Concerns have been voiced about the required minimum binocular overlap as well as the possibility that perceptual artifacts such as binocular rivalry — referred to as "luning" — may have an adverse impact on pilot performance. Although the studies found image fragmentation did place some workload on the pilot/test subjects,[61,62] all were conducted using static imagery. Several techniques have been effective in reducing the rivalry effects and their associated perceptual artifacts.[63]

It should be kept in mind that the resolution of the VCS is a product of the resolution of the HMD and of the imaging sensor. While an HMD with very high resolution may provide a high-quality image, pilotage performance may still be limited by the resolution of the imaging sensor such as the FLIR or camera. In most cases, it is preferable to match the field of view of the HMD with that of

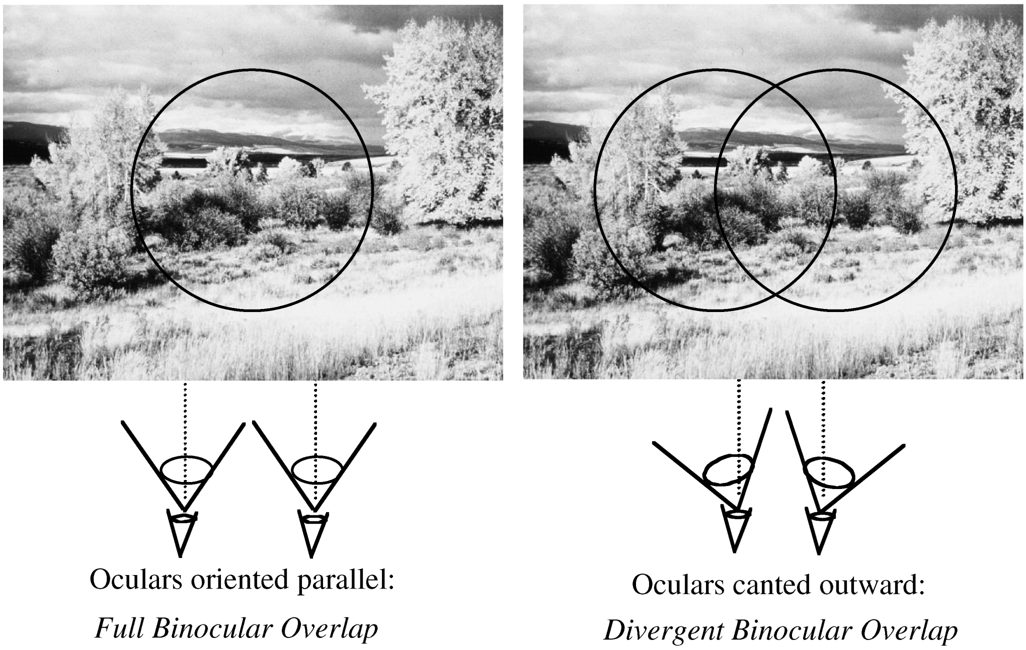


FIGURE 5.14 Comparison of a full binocular overlap and divergent partial binocular overlap. Note the increase in viewable imagery in the horizontal direction with the divergent overlap.

the sensor to achieve a 1:1 correspondence between sensor and display to ensure an optimum flying configuration.

5.4.3 Luminance and Contrast in High Ambient Luminance Environments

In the high ambient luminance environment of an aircraft cockpit, daylight readability of displays is a critical issue. The combining element in an HMD is similar to the combiner of a HUD, reflecting the projected imagery into the pilot's eyes. The pilot looks through the combining glass and sees the imagery superimposed on the outside world, so it cannot be 100% reflective — pilots always prefer to have as much see-through as possible. To view the HMD imagery against a bright background such as sun-lit clouds or snow, this less-than-perfect reflection efficiency means that the image source must be that much brighter. The challenge is to provide a combiner with good see-through transmission and still provide a high-luminance image. There are limitations, though, because all image sources have a luminance maximum governed by the physics of the device as well as size, weight, and power of any ancillary illumination. In addition, other factors such as the transmission of the aircraft canopy and pilot's visor must be considered when determining the required image source luminance, as shown in Figure 5.15.

The image source luminance (B_I) is attenuated before entering the eye by the transmission of the collimating optics (T_O) and the reflectance of the combiner (R_C). The pilot views the distant object through the combiner (T_C or $1 - R_C$), the protective visor (T_V), and the aircraft transparency (T_A) against the bright background (B_A). We can calculate the image source luminance for a desired contrast ratio (CR) of 1.3 using the expression:[11]

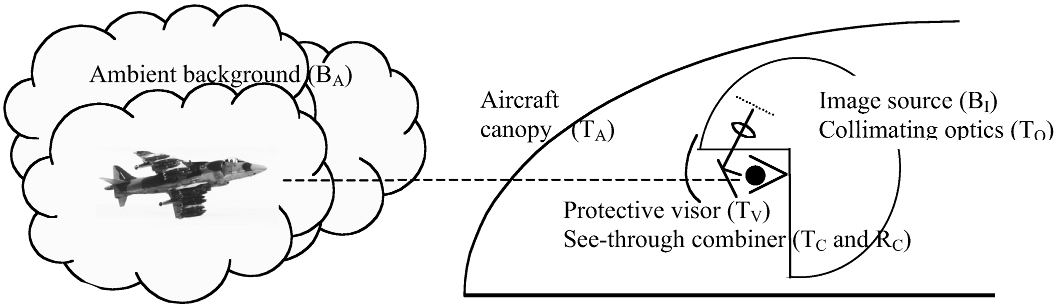


FIGURE 5.15 Contributions for determining image source luminance requirements for an HMD in an aircraft cockpit.

$$CR = \frac{B_A + B_{Display}}{B_A}$$

where we know that the display luminance to the eye is given by:

$$B_{Display} = B_I * T_O * R_C$$

and, as observed by the pilot, the background is given by:

$$B_O = T_C * T_V * T_A * B_A$$

Rewriting, we can see that:

$$CR = \frac{1 + B_I * T_O * R_C}{T_C * T_V * T_A * B_A}$$

We can substitute some nominal values for the various contributions as given in the following table:

TABLE 5.5 Contributions for the Display Luminance Calculations for Four Different HMD Configurations

		Case 1 — Clear Visor, 50% Combiner Transmission	Case 2 — dark Visor, 50% Combiner Transmission	Case 3 — Clear Visor, 80% Combiner Transmission	Case 4 — Dark Visor, 80% Combiner Transmission
Optics transmission	T_O	85%	85%	85%	85%
Combiner reflectance	R_C	50%	50%	20%	20%
Combiner transmission	T_C	50%	50%	80%	80%
Visor transmission	T_V	87%	12%	87%	12%
Aircraft canopy transmission	T_C	80%	80%	80%	80%
Ambient background luminance	B_C	10,000 fL	10,000 fL	10,000 fL	10,000 fL
Required image source luminance	$\mathbf{B_I}$	**2,456 fL**	**339 fL**	**9,826 fL**	**1,355 fL**

The first two cases compare the difference when the pilot is wearing a Class 1 (clear) vs. a Class 2 (dark) visor.[64] The dark visor reduces the ambient background luminance, improving HMD image contrast against the bright clouds or snow. These first two cases are relatively simple because they assume a combiner with 50% transmission and 50% reflectance (ignoring other losses). Since pilots need more see-through, this means a reduced reflectance. Cases 3 and 4 assume this more realistic combiner configuration with both clear and dark visors, resulting in a requirement for a much brighter image source.

One of the ways to improve both see-through transmission and reflectance is to take advantage of high-reflectance holographic notch filters and V-coats. The problem is that while these special coatings reflect more of a specific display color, they transmit less of that *same* color, which can alter perceptions of cockpit display color as well as external coloration.

5.5 Summary

Head-mounted displays can provide a distinctly unique and personal viewing experience no other display technology can match. By providing the pilot with display information that is linked to head orientation, the pilot is freed from having to return his attention to the cockpit interior and is able to navigate and fly the aircraft in a more intuitive and natural manner. This is an effective means of providing a pilot with aircraft status as well as information about the surrounding airspace.

But these capabilities are not without a price. HMDs require careful attention to the complex interactions between hardware and human perceptual issues, made only more complex by the need for the HMD to provide life support in an aviation environment. Only when all factors are considered and the requirements successfully suboptimized with an understanding of the aviator's tasks and environment, will this be accomplished.

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