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Chapter 2

VISUAL DISPLAYS: HEAD-MOUNTED DISPLAYS

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Head-mounted displays (HMDs) came from the future—devices to envelop our eyes and ears and cloister us from the real world while immersing us in computer-generated fantasies limited only by our ability to algorithmically create them.

Looking back 40 years to Ivan Sutherland's (1963) "Sketchpad," it is easy to see that HMDs quickly progressed from science fiction to delivering grounded results. Systems are now used to visualize the placement of instruments in automobile interiors, to decide where to sink the next oil well, and to train personnel in virtual scenarios too dangerous for actual practice.

It is sometimes difficult, however, to separate the promise of these devices from the reality of their performance—especially when considering training applications that must accurately represent specific and well-defined environments. What makes this particularly vexing is that, while technical specifications can easily be compiled, it is difficult to understand the usefulness of these specifications with respect to a training system's effectiveness. Some specifications just do not matter, while others create artifacts that, while hard to predict, can make or break a system.

This chapter attempts to increase the decision maker's understanding by interpreting the user's experience of HMD technologies. It gives an overview of the physical, cognitive, and perceptual ramifications of common HMD choices and describes current design and technology examples. Readers interested in more detailed information are encouraged to look at *Head Mounted Displays: Designing for the User* by James E. Melzer and Kirk Moffitt (1997).

WHY CHOOSE AN HMD?

When creating display systems for immersive training applications, it is useful to think of an HMD as mapping pixels from its microdisplays out into a hypothetical three-dimensional virtual environment. For example, if the goal is to train a user how to fix an engine, then the pixels would best be placed in a manner representing an engine—a few feet away from a user and concentrated in a small area. If, however, the goal is to familiarize a user with a dense urban area, then the pixels would need to panoramically span a virtual area the size of a few city blocks. For a screen based display, the engine application might use a single large stereoscopic screen placed in front of the user, while the city would require a large multiscreen panoramic configuration.

This model of mapping pixels to a virtual environment's objects can be used to consider characteristics unique to HMDs when evaluating display systems for the following specific training tasks:

Flexible—As the above two examples highlight, the physical topology and required distribution of mapped pixels in a virtual space can vary greatly between different applications. HMDs can easily accommodate a range of training scenarios because they are available with a wide range of resolutions and fields of view. These choices allow the designer to tailor the display for the application at hand and to modify such choices to follow the demands of evolving system requirements.

Efficient—Because HMDs use head tracking to display imagery from the user's current point of view, they make the most out of every pixel they are fed. In contrast, a screen based system must render and display pixels everywhere, even if the user is not looking in that direction. Since the displays travel with the user's head, HMDs carry pixels to where they are needed, effectively multiplying resolution. For example, a single $1,280 \times 1,024$ HMD with a 60 degree field of view will fill a 360 degree virtual sphere six times over, thus effectively providing $7,680 \times 6,144$ accessible pixels over the sphere. Not only does this make efficient use of the displays, but it allows a single rendered viewpoint to provide imagery that normally would require six viewpoints.

Deployable—By decreasing the rendering requirements, HMDs can often be driven by a single laptop computer. This means an HMD, rendering computer, and head tracking system can fit in a single briefcase. In addition to simplifying maintenance and spares, many HMDs are designed to operate with no need for alignment and calibration—they can be easily carried to a location, turned on, and made ready to go.

Potent—By occluding the user from the real world and substituting a virtual world, HMDs exhibit a type of "perceptual potency" that is hard to duplicate with any other technology. In many virtual environment configurations, users can see their own body, physical details of the display system, and portions of the surrounding environment. While useful for some applications, such real world cues can detract from fully transporting a user to a virtual world. HMDs are often configured to completely cloister a user—to algorithmically control everything the user sees and hears.

This potency comes with a corresponding demand—the complete system must accurately portray the virtual environment and keep pace with a user's motion and expectations. For example, poor tracking and slow update rates cannot be tolerated as they degrade cues important for maintaining a sense of balance.

Such potency can be useful in scenarios developed to elicit strong responses. A classic example is found in experiments incorporating a virtual "pit room" that appears to the user as a ledge above a 20 foot virtual drop to a room below. Most users experience a strong sense of physical danger when observing the virtual pit from their apparently precarious standpoint on the ledge (Meehan, Insko, Whitton, & Brooks, 2002).

Accurate—User-specific imagery needs to be generated for every head position in a virtual environment because each user must see the scene rendered exactly from his or her perspective or the synthetic images will not match the user's movements. Such a mismatch can result in inaccurate and possibly misleading imagery. Screen based displays can easily accommodate a single head-tracked user, but multiple users pose problems due to the fact that participants in these systems are all looking at the same physical screens (Agrawala et al., 1997). HMDs have the luxury of providing each user with a personal display, each tracked to account for an individual's head position and orientation. As such, HMDs allow all participants in a training environment to be surrounded by accurate, perspective-correct imagery.

Observable—Because HMDs are tracked, they can easily be used to observe where the user is facing in an environment. For example, DaimlerChrysler Motors Company LLC employed a mechanically tracked HMD to enable ergonomic studies of proposed designs for automotive interiors. By being able to observe the view as seen by different-sized drivers, engineers were able to determine optimal sight lines and component placement (Brooks, 1999). This is particularly interesting in training applications that require a correlation between trainees' actions, their orientation, and what they actually see.

Available—The rising demand for consumer-grade digital entertainment technologies has led to the development of components that HMD based training systems have used to move beyond fiction into useful tools. Graphics technologies for video games have led to easier and lower cost modeling and rendering of synthetic worlds. The digital production of movies has led to the development of high performance motion-capture and tracking systems. The home-theater display market has created high resolution microdisplays that can be repurposed for HMDs. As such, tracking, rendering, and displays have reached a critical price-performance ratio that now enables HMDs to be cost-effectively applied to a number of new applications (Brooks, 1999).

HMD DESIGN CHARACTERISTICS

When matching HMDs to specific training tasks, it is instructive to recognize that HMDs are intimate interface devices—almost like pieces of clothing—and that there is a wide variety of design choices affecting function and comfort that can best be judged by simply trying the HMD on and looking around. Just as soldiers should "train as they fight," HMDs should be evaluated "as they will train." If this firsthand experimentation is done in a perceptually engaged and critical manner, decision makers can avoid prejudgments. It is easy to allow data sheets and specifications to cloud one's judgment and accept defects that are the result of poor design trade-offs or a limited range of adjustment. It cannot be overstated that while there are some stunningly good HMDs available, there are also stunningly bad ones as well. Toward this end, it is useful to consider the interplay between design choices and their optical, physical, and cognitive effects.

Overview of Visual Issues and Terms

Functionally, HMDs are similar to looking at a small display with a magnifying glass and then holding the display and magnifier up to the eye. The magnifier enables the user to focus on the display as it is brought closer to the eye. The closer to the eye it gets, the larger the image appears because it replaces more of the real world with the image from the display.

As such, the optical goal of an HMD is to make a small display appear large (*optical magnification*) and to subtend a large portion of a user's view (*field of view*). This is typically accomplished by either employing optics similar to a magnifying glass (*simple magnifier*) or a microscope (*compound optics*).

A quick feeling for the visual issues associated with HMDs can be had by considering a pair of binoculars. Binoculars must be held a certain distance away from the user's eyes (*eye relief*) and adjusted to align with the distance between the eyes (*interpupillary distance or IPD*). This alignment places the user's pupils within the small region in front of the lens, which provides a clear view of the magnified image (*eye box or exit pupil*). The lenses are then focused to place the magnified image at a virtual distance in front of the user (*focal plane*) that both eyes can focus upon (*accommodate*) and allow the eyes to triangulate (*converge*) on objects to form a stereoscopic view. Some binoculars, especially lower cost ones, will exhibit visual artifacts or *optical aberrations*. In HMDs, these artifacts include a rainbow effect (*chromatic aberration*), many types of blur (*spherical aberration, coma, astigmatism,* and *field curvature*), and warped appearance (*geometric distortion*). Readers interested in a classic text on optics design are encouraged to look at Warren J. Smith's (2000) *Modern Optical Engineering*. An excellent overview of HMD designs is presented in *Head-Worn Displays: A Review* by Cakmakci and Rolland (2006).

Exit Pupil (Eye Box)

Compound optics form a relatively small region called the exit pupil, which can be thought of as a small hole that is located slightly in front of the eyepiece. When the eye's pupil is aligned with the exit pupil, a clear image is seen. If the eye's pupil moves out of this region, light from the display becomes occluded: a portion of the image goes dark and often exhibits a characteristic kidney bean shape. The size of the exit pupil is constrained by the physics of the optical system. Small exit pupils generally allow for more aggressive optical designs, but are undesirable as they require careful alignment of the HMD with respect to a user's eyes.

Alternatively, simple magnifying optics are classified as nonpupil forming and deliver a comparatively large region where the eye will see a sharp magnified image from the display—similar to looking through a magnifying glass. Although simple magnifier designs have an ideal position for the user's eye (it lies along the optical axis of the eyepiece), the less ideal positions result in a slight blurring of the image that does not go dark and tends to degrade more gracefully than those of pupil-forming systems. Simple magnifiers, however, often require the use of larger optical components and displays.

On some HMDs with small exit pupils, the user will see a good image while looking forward, but a glance to the side will make the image go dark. The eye's pupil is located toward the surface of the eyeball, so a rotation of the eye causes the pupil to translate away from the exit pupil of the optics because the eye's center of rotation is located behind the pupil. It is important to pay attention to this on wide field of view (FOV) HMDs that claim a field of view that is mathematically correct but impossible to achieve by some users when they actually look toward the edges of a scene.

Interpupillary Distance Adjustment

Narrow exit pupils often require the left and right display optics to be closely aligned with the user's left and right eyes. Such an adjustment feature is often desired for compound optical systems. Typically, the IPD range for HMDs is specified as the total IPD, and HMDs may either adjust each display or the total IPD. IPDs vary across the population and generally range from 53 millimeter (mm) to 73 mm with an average of 63 mm (Kalawsky, 1993).

Should IPD adjustment be possible, care must be taken to reset it for each participant; otherwise the situation can be made worse due to the wide range of IPDs. A test pattern displayed on the HMD can be used to set the IPD; however, some users find it confusing so it may be advantageous to numerically set the IPD before the user puts on the HMD. In this case, an interpupilometer (a common piece of ophthalmic equipment) may be used to accurately measure the user's IPD without requiring the user's judgment. Most software used to render virtual imagery assumes an average IPD of 65 mm; ideally, however, it should incorporate specific users' IPDs as well. Simple magnifier systems can be designed to enable a wide range of IPDs with minimal image degradation, and some can be used without the need for IPD adjustments.

Accommodation and Convergence

When the eyes fixate on an object, a number of physiological actions occur. The two primary actions are the physical focusing of the eyes' lenses to accommodate the object and the action of differentially rotating each eye to converge on the object. The rendering of the virtual environment considers the slight viewpoint differences between a user's two eyes and draws near-field imagery with an offset between the left and right eyes. When viewing this pair of images, the user's eyes must rotate by different amounts based on how close each virtual object is—an object at infinity requires no convergence, while an extremely close object requires "crossed eyes." The stereoscopic nature of an HMD is derived from this effect.

HMDs magnify a microdisplay, thus fixing the focal depth of the pixels. As such, the distance at which the user's eyes accommodate when looking at a virtual object cannot be adjusted by the computer to correspond to its virtual distance. This creates a mismatch between the convergence cues that are rendered correctly and the accommodation (focus) cues that are fixed by the HMD optics.

This is a current limitation of commercially available HMDs and an area of active research (Akeley, Watt, Girshick, & Banks, 2004; Rolland, Krueger, & Goon, 2000). Screen based displays share this characteristic—the user accommodates on the surface of the screen, while trying to converge at the distance of the virtual objects. Some HMDs may be focused at different fixed depths and thereby be optimized for near-field or far-field training tasks.

Field of View

A user's natural FOV is constrained by the shape of the skull and the eye socket, with the nose blocking the central portion. This can be seen by closing one eye and looking around the periphery. For most people, the FOV of each eye is 120° vertical and 150° horizontal. The combined field from both eyes is 200° with a 100° *binocular overlap* region that provides stereoscopic cues (Velger, 1998). These metrics vary significantly based on face geometry, age, and eye characteristics.

For a given lens diameter, the closer the lens is to the eye, the larger the potential field of view. This can be observed by moving one's palm nearer to and away from the face. Assuming one could focus on the palm, it is clear that it needs to be touching the face to come close to subtending the full field of view of one's eye. Very wide FOV HMDs are constrained practically by the diameter of the optics and how close a user's eyes can be to the eyepiece.

The left and right eye images of many narrow FOV displays present to exactly the same region of a user's FOV. This arrangement is said to be 100 percent overlapped, and, except for differences due to stereo parallax, the images for each eye appear to be superimposed on each other. One approach to achieving a larger total field of view is to not fully overlap the images. This provides a central region with stereoscopic imagery, and peripheral regions without stereoscopic imagery. Wide FOV designs tend toward this arrangement, which is appropriate given its match with the human visual system and facial geometry.

Wide Fields of View

Narrow FOVs appear to force unnatural head and body movements while also limiting the natural motion of the eye. This need to move the head and body to explore a scene can be demonstrated by curling the fingers and touching the index and ring fingers to the thumb on both hands to create two cylinders. Holding the hands up to the face like a pair of virtual binoculars creates a resulting FOV approximating 45° per eye.

Tasks such as walking are possible with narrow displays, however, performance is greatly improved with a wider field of view display (Arthur, 2000). Melzer and Moffitt (1997) present a summary of papers that generally indicates that wider FOVs result in better performance for tasks requiring ego orientation, locomotion, and reaching, including orientation and navigation within an environment. A wide FOV also appears to be instrumental in establishing situational awareness. Melzer and Moffitt found that it helps "the user to establish visual position constancy and to understand events that occur over a panoramic visual field" (p. 224, per Wallach and Bacon, 1976).

Optical Artifacts

The art of optical design involves balancing such issues as cost and exit-pupil size with such visual artifacts as aberration and distortion. The question is not whether such artifacts are present, but whether the magnitude is great enough to detract from the goals of the training application. It is often the case that slight yet noticeable optical artifacts are unimportant, while features such as a light system weight or a wide FOV are mandatory.

Chromatic aberrations are caused by the dispersion of light through optical materials. They are particularly noticeable with thick or plastic lenses and are usually seen as a rainbow effect around the edges of the image. While these could be reduced with software techniques, they are not of primary concern with most modern HMDs. Geometric distortions are a warping of the image and can take many forms, including an outward warp called pincushion distortion or an inward warp called barrel distortion. These can be reduced through computation (Robinett & Rolland, 1992). Such correction is now being integrated directly into some HMD electronics or may be implemented as part of the software application. It is not easy to correct for the many types of optical blur that are inherently linked with the quality of an optical system's design. It is a multidimensional issue that can take many forms and is difficult to understand intuitively. As such it is best qualified through personal observation rather than solely through numerical specification.

Of particular concern are artifacts that cause visual discomfort. Most important among these are artifacts that cause incorrect imagery in the region of binocular overlap. These cause the eyes to strain as they attempt to correlate imagery seen by the left and right eyes. While such effects can be the result of poor optics, they are often caused by a physical misalignment that occurs over time and must be monitored by the system operator. Additionally, rendering software must be tested for accuracy in this regard. Misaligned imagery—including swapping eyes—is a common source of discomfort that lies with the software and complete system, not the HMD.

Resolution

Although the resolution of HMDs is most often described like a standard computer monitor (total number of horizontal and vertical pixels), the resolution of an HMD is best considered by the angle subtended by a given pixel, typically measured in minutes of arc and called the *angular resolution.* Values below three or four arc minutes per pixel begin to appear relatively crisp with human vision capable of better than one arc minute (National Research Council, 1997).

For a given display resolution, a narrow FOV HMD will create better angular resolution as it concentrates pixels in a smaller angle. In this way, a wide FOV will degrade the angular resolution. This can be mitigated with optical designs that create variable angular resolution across the field of view—the central region having better resolution than the periphery.

Optical artifacts, such as blur, can decrease the effective resolution. As such, a single-number specification for resolution should be but one of the metrics used when considering HMDs.

Weight

Specifying weight is similar to resolution: while lighter is obviously better, it is only one measure of how useful an HMD will be in practice. It must be balanced against the often competing physical characteristics of balance, rotational inertia, fit, and form.

Balance affects the downward rotational force placed on the neck. A 500 gram HMD with all the weight in the front will be more uncomfortable than a well-balanced 1,000 gram design. There are many approaches to counterbalancing an HMD that range from simply adding weight at the rear to complex optical configurations that fold the optical path around the head to locate mass away from the face, moving it backward and toward the sides of the head. Unfortunately, moving weight in this manner can increase rotational inertia—the amount of force a user will need to exert when quickly looking around. This is an important consideration for training applications that require rapid head motions approaching 1,000° per second squared (Bolas & Fisher, 1990).

Form

As discussed, some optical designs require that the HMD optics be well positioned relative to the wearer's eyes to within millimeters. The HMD needs to accurately hold electronics, optics, and displays, and it must adjust to fit a wide range of human heads with a firm grip that does not allow the system to slip during rapid head motions. There is a variety of mounting techniques that can best be judged by having a variety of users wear the system.

The physical form of the display needs to be considered with the target application in mind. For example, driving simulation and rifle training applications often use physical props that must be held close to the user's head. As such, the

HMD cannot extend far away from the user's face or it will interfere with a real steering wheel or gun sight.

Additional form considerations include the time it takes to fit and don an HMD, and making sure the HMD is compatible with required gear such as helmets and jackets and that it will not snag on cables or cloth. Ventilation, heat, and compatibility with the user's eyewear are additional concerns.

EXAMPLES

Optical Approaches

Wide Field of View

In 1985, NASA (National Aeronautics and Space Administration) Ames Research Center created a wide FOV HMD by integrating optics for viewing film based stereoscopic pairs (originally for the large expanse extra perspective [LEEP] wide-angle camera system) with liquid crystal display (LCD) panels that were roughly of the same size. This configuration was commercialized in the VPL Research, Inc. EyePhone, Fakespace Labs BOOM, and Howlett LEEP Video System I. Consumer-priced narrow FOV displays in the late 1990s (for example, the Sony Glasstron) turned attention away from immersive wide FOV displays toward narrow FOV designs more suitable as monitor replacements. This led to wide FOV HMD designs remaining largely static until the mid-2000s.

The recently introduced Fakespace Labs Wide5 provides a FOV exceeding 150°. A large pupil is created by incorporating modern LCD panel technologies and a single lens design. It originally was designed to provide a robust and portable virtual training system that could easily be deployed in the field for close-quarters battle training applications as part of the U.S. Navy's virtual training and environments program. To meet those requirements, it can be mounted to helmets with a standard night vision mount and incorporates a custom interface deriving stereoscopic pairs from a single digital visual interface signal available from a laptop. To increase the perceived resolution, the Wide5 has higher pixel density toward the central region.

Tiled Designs

Wide FOV HMDs can be created by tiling a number of smaller displays in a concave form in front of each eye. Tiles are composed of a display module and eyepiece optics that butt together and cover a portion of the perceived field of view. These displays generally require precise adjustment when the HMD is placed on the head to reduce visual tiling artifacts—the eyes must be aligned with each microdisplay and lens. Each microdisplay typically requires a video source, thus six displays per eye require 12 rendered viewpoints, making computing demands a significant system consideration, but also increasing resolution.

Kaiser Electro-Optics (now part of Rockwell Collins) created a display under contract to the Defense Advanced Research Projects Agency Electronic Technology Office in the 1990s incorporating a three by two matrix of displays for each eye. This display used small LCD displays driven by 12 separate graphics inputs. The resulting field of view was over 153° horizontal by 48° vertical (Arthur, 2000). Sensics Inc. has created a tiled display that uses a matrix of displays to create a wide FOV virtual image. Organic light-emitting displays (OLEDs) are used in a modular approach so the display may be configured in a variety of different ways, including a seven by three per eye arrangement of displays to provide a total of 4,200 × 2,400 pixels. In this tiled configuration, all 21 optical and display assemblies have to align with each of the user's eyes. This family of HMDs can be configured with fields of view ranging from 72° to 179° horizontal by 30° to 60° vertically.

High Resolution Inserts

The human eye has superior visual acuity in a small region known as the fovea. A few HMDs have been created that employ a wide field of view display coupled with a second display tracked to the fovea. This results in a wide FOV immersive experience, enhanced with the precision and clarity typical of narrow FOV displays. The implementation of this is complex as it requires tracking of the eye. There have been very few systems fielded using this approach. CAE created such a system used for helicopter simulation in 1981 (Velger, 1998).

Medium Field of View Displays

One of the earliest examples of an HMD used for virtual environment visualization was built in 1968 as part of Ivan Sutherland's groundbreaking work. This system used half-inch monochrome cathode ray tube (CRT) displays that provided a 40 degree field of view per eye. The image was reflected from partially silvered mirrors creating an augmented reality display system.

The Virtual Research V8 design and the NVIS, Inc. SX display are both popular displays in this range of FOV. The NVIS SX offers a horizontal field of view of 48.5° and vertical of 39.6° and uses 1,280 × 1,024 field sequential color ferroelectric liquid crystal on silicon (FLCOS) panels. The V8 uses lower resolution transmissive LCDs and has a horizontal field of view of 49° and vertical of 33°. Both weigh over two pounds. Typically, adjustment of the IPD is needed to achieve the best quality image and to reduce artifacts as the eye moves.

Rockwell Collins makes several HMDs in this FOV range. Its SIM EYE product employs a see-through optical design with the displays located to the sides of the head, and relay optics deliver the images to semitransparent eyepieces. Independent IPD adjustment is provided for each eye.

Narrow Fields of View—Personal Display Monitors

HMD with fields of view of around 25° are available at a fairly low cost. Most employ OLED or small LCD displays coupled with magnifying optics. Examples include OLED displays by eMagin Corporation and LCD based Vuzix (Icuiti) designs. Daeyang and IODisplays use liquid crystal on silicon (LCoS) displays and reflective magnifying designs. While many of these come bundled with head-tracking technologies, they are of limited utility for fully immersive training applications due to the restricted field of view. By way of example, a 25 degree FOV is equivalent to viewing a 21 inch monitor at 4 feet.

Alternative Optical Approaches

An HMD that incorporates a head-mounted projector uses a very different optical path. The projector directs an image from the user toward a retroreflective material that reflects the image back toward the user's eyes. This approach has shown promise for cockpit displays and other applications in which a type of virtual overlay can be implemented with cut sheets of retroreflective material (Fergason, 1997).

Displays that provide the user with multiple planes of focus are not yet practically deployed, but encouraging research by Akeley et al. (2004) shows that a subset of planes can be used to create a display that could alleviate some of the issues associated with the accommodation and convergence issues discussed previously.

HMDs that mix real world and virtual imagery provide many unique advantages. These are described in Henderson and Feiner, Volume 2, Section 1, Chapter 6—"Mixed and Augmented Reality for Training."

Display Technologies

The display requirements for HMDs are demanding because, ideally, they would be light and exhibit very high resolution, color depth, brightness, and contrast while using little power and creating few temporal artifacts. Naturally, achieving all these requirements simultaneously is challenging, and designers resort to the best solutions available at the time in the context of their overall system goals.

Field Sequential Liquid Crystal on Silicon Color Displays (FLCOS)

FLCOS displays reflect light, and the polarization of pixels controls brightness. These displays employ front illumination with a separate field sequential color light source. Such field sequential displays as FLCOS show a sequence of primaries for each pixel and the eye's persistence of vision integrates the sequential presentation of the colors and perceives the image in full color. Visual artifacts from field sequential color displays are generally not objectionable in narrow field of view conditions. In wide FOV HMDs, color flicker is an issue for some users as peripheral vision is more sensitive to motion and flicker.

Active-Matrix Liquid Crystal Displays (AMLCDs)

These displays are like those used in laptop screens and are typically thin-film transistor transmissive displays illuminated by a backlight. Pixels are composed of three subpixels (red, green, and blue). AMLCD displays are made by a variety of companies; Kopin Corporation makes very high resolution displays suitable for HMDs. A fast response time is needed to reduce the smearing of moving objects.

Organic Light-Emitting Displays (OLEDs)

OLEDs emit light from their surfaces, which enables both truer blacks and more compact optical designs because there is no backlight assembly. eMagin Corporation is currently the primary source for small form factor pixel-type displays. These displays are new, and improvements in lifetime, resolution, and size are expected.

Alternative Display Technologies

Several companies have made use of fiber-optic image pipes that decouple the display from the HMD. Laser based systems that project directly onto the retina will no doubt be part of the future HMD landscape. Microvision, Inc. continues to innovate with such laser based projectors. HMD designs have largely moved away from cathode ray tubes.

Mounting Approaches

Generally, a person can comfortably carry an additional 10 percent of his or her head weight for indefinite periods. As the typical head weighs approximately 10 kg, it is desirable to have an HMD that weighs less than 1 kg (kilogram). A brief overview of the numerous techniques that have been developed to mount HMDs follows.

On-Head Mounts

Spectacles—These designs are suitable for narrow field of view displays where the weight is minimal and the narrow field of view is achieved with small plastic lenses. FOV is under 30° and the weight is typically under a few ounces. The Vuzix (Icuiti) products are good examples.

Forehead Rest—HMDs like those from IODisplays and eMagin weigh around six to eight ounces and use more complex optics. The displays have a pad resting on the frontal bone and a strap around the back of the head and sometimes one over the crown of the head. The strap needs to be tight to create friction on the forehead mount, but provides purchase for the HMD.

Scuba Mask—Older systems, such as that from VPL, used heavier displays held on the face by a large contact area and a tight head strap grabbing the back of the head. This design adds a minimal amount of additional weight; however, the strap-type adjustment is inconvenient and has to be tight to hold the HMD in place. They often provide poor ventilation and can become humid.

Helmet Based—Kaiser Electro-Optics SIM EYE and L3 advanced helmet mounted displays (Sisodia et al., 2007) mount directly to a training or flight helmet; these designs permit the use of the pilot's own helmet. Typically there would be several sizes and helmet designs that need to be supported.

Head Strap—Fakespace Labs Wide5 and Virtual Research V8 incorporate a ratchet-style head strap that can be tightened to hold the HMD on securely to fit most people. This strap design does not grab the occipital so these work best with a counterweight. This design is relatively easy for the person wearing the HMD to adjust.

Exoskeletal—Disney, Kaiser Electro-Optics ProView, and other designs have employed a ridged exterior and a supple interior strap. The advantage is that the rigid exterior frame helps transfer the load of the HMD to the head strap and head in multiple places.

Webbing—SEOS Limited and others hang the HMD around the head and aim to balance the straps holding on the HMD. These designs get heavy rather quickly, are cumbersome to put on and remove, and are hard to keep accurately aligned with the eyes.

Over the Head with Rigid Frame—Sensics and Keio University Shonan Fujisawa Campus use designs that capture the occipital and leave the area near the ears unencumbered. These and other systems that are not counterweighted need to be tight in the back, and, consequently, are most easily adjusted by another person.

Counterbalanced Approaches

A number of display environments (for example, those designed for a seated user) do not require free movement while the user wears the HMD. In these situations, there may be advantages to counterbalancing the mass of the HMD with an external mechanical structure. This reduces the weight of the HMD on the user and may also afford precise tracking. Examples include the Fakespace BOOM and Disney's Aladdin ride, which used a cable system to counterbalance the displays.

CONCLUSION

To select an appropriate HMD, the decision maker will find it informative to physically try the display to fully gain an appreciation of its functionality and to spend time in the HMD, looking all around the image and questioning the effects. As discussed in this chapter, many of these effects and artifacts are quite subtle and require an engaged and observant test of the display as described here.

Step One: Don the HMD and move in a manner similar to the training application, paying attention to the effect of rapid or unusual exploratory motions. In addition to feeling for any uncomfortable physical sensations, such as looseness or offset center of mass, pay particular attention to the virtual images, looking for a bright and sharp environment across the entire field of view. An important step is to refit the helmet as often as required to optimize the experience.

Step Two: Now with the HMD properly fit, close and relax the eyes for 20 seconds, then look straight ahead for 10 seconds and roll the eyes around to explore the edges of the environment. Rotate the head and explore the environment in a manner consistent with the training application. Pay attention to optical artifacts that cause visual discomfort or that create a misleading virtual environment. It is often useful to alternate closing the left and then the right eye to look for differences, both while fixating on specific objects and while independently exploring the field of view for each eye.

When properly selected and integrated, HMDs leverage emerging technologies to create efficient and flexible training applications that are easily deployed. With the ability to completely cloister a user in a synthetic environment, HMDs can enable the development of virtual training scenarios that are impractical to duplicate in the real world.

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