Head-Mounted Display Systems

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INTRODUCTION

Real-time three-dimensional (3D) interactive displays refer to display devices servo to the line of sight of a user, allowing not only free head motion, but also potentially and importantly full body mobility. Ideally, one could wish for such capability to exist without the need to wear any view-aided device. However, unless a display system could be created in space, anywhere and anytime, a simple solution is to wear the display. Such displays are today rather referred to as head-worn displays, but historically they have been referred to as head-mounted displays (HMDs). Because humans have not evolved to wear heavy devices, the challenge of interfacing such displays to the human head is tremendous, given that the challenge is to design HMDs with lightweight optics as well as lightweight and ergonomic optomechanical headsets. Because some of the display specifications play against each other in achieving a lightweight and ergonomic display, it is critical to drive such display design with targeted applications and associated tasks that will help prioritizing the display requirements.

This entry starts with a historical note and a perspective on contemporary pursuits in HMD designs. The main focus then shifts to details of the various components of HMDs, including the light source, various approaches to the optical design, and key aspects of the user interface. We then briefly review existing displays for both immersion and mixed reality. The final part discusses advanced pursuit in HMD designs.

Historical Note

An HMD may be thought as the ViewMaster of virtual environments (VEs), where the simple stereoscopic slides have been replaced by miniature electronic displays similar to those placed in camcorders, and the displays and the optics are headband or helmet mounted. HMDs may first be distinguished from a user perspective by being monocular (i.e., one-eye display), biocular (i.e., the same image presented to both eyes), or binocular (i.e., stereoscopic images). Such distinction is critical to enabling different perceptions; however, the optics designs associated to each eye across these configurations have much commonality.

The first graphics-driven HMD was pioneered by Ivan Sutherland in the 1960s.[1] The acronym HMD has been used since to also refer to within military applications to helmet-mounted displays, where the display is attached to a military helmet.[2,3] The U.S. Army flew a hemlet-mounted sighting system on the Cobra helicopter, and the Navy shot missiles using HMDs in the 1960s. The Integrated Helmet And Display Sighting System (IHADSS) was then deployed by the U.S. Army on the AH-64 Apache helicopter.[4] The IHADSS, while monocular, greatly contributed to the proliferation of all types of HMDs. An ergonomically designed headband that properly secures the display on the user's head is perhaps one of the biggest challenges for designers of HMDs, a challenge that is intrinsically coupled to that associated with the optical design. Finally, the idea of Sutherland to couple the HMD with tracking devices has set a vision for generations to come.

CONTEMPORARY PURSUIT

The contemporary interest in VEs has been stimulated since its beginning by the advent of sophisticated, relatively inexpensive, interactive techniques allowing users to move about and manually interact with computer graphical objects in 3D space. The technology of VEs, including HMDs, has since undergone significant advancements and various technologies have emerged.[5–7]

A recent taxonomy of HMDs, which has been broadly adapted to other senses beside the visual sense, is the one based on the reality-virtuality (RV) continuum,[8] with at one end immersive displays that enable 3D visualization of solely simulated VEs, and at the other, displays that solely capture real environments, and in between see-through displays that blend

Encyclopedia of Optical Engineering DOI: 10.1081/E-EOE-120009801

real and graphical objects to create mixed reality (MR). Applications driving these various technologies abound.[9–12] One of the grand challenges is the development of multimodal display technologies allowing spanning the RV continuum.[13] Other grand challenges further discussed in this article are foveal contingent, multifocal plane, and occlusion displays.

FUNDAMENTALS OF HEAD-MOUNTED DISPLAYS

Per eye, an HMD is composed of a modulated light source with drive electronics viewed through an optical system, which, combined with a housing, is mounted on a user's head via a headband or a helmet. The positioning of light sources, optics, and optomechanics with respect to the head inflicts tight requirements on the overall system design. Moreover, to create appropriate viewpoints to the users based on their head position and possibly gaze point, visual coupling systems (i.e., trackers) must be employed. The finding that tracking errors predominately contributed to visual errors in augmented reality displays led to extensive research in improving tracking for VEs in the last decade.[14–15]

Emerging technologies include various microdisplay devices, miniature modulated laser light and associated scanners, miniature projection optics in place of eyepiece optics, all contributing to unique breakthroughs in HMD optics.[16–17] More subtle perhaps yet critical changes across various HMDs lie in the choice of the optical component in front of the eyes in folded designs or HMD combiner. We now discuss the various components of HMDs: the microdisplay sources, the HMD optics, and the human-visual system HMD–optics interface.

Microdisplay Sources

In early HMDs, miniature monochrome CRTs were primarily employed. A few technologies implemented color field-sequential CRTs. Then, VGA (i.e., 640 × 480 color pixels) resolution Active-Matrix Liquid-Crystal-Displays (AM-LCDs) became the source of choice. Today, SVGA (i.e., 800 × 600 color pixels) and XGA (i.e., 1280 × 1024 color pixels) resolution LCDs, Ferroelectric Liquid Crystal on Silicon (FLCOS),[18] Organic Light Emitting Displays (OLEDs),[19] and Time Multiplex Optical Shutter (TMOS) [20] are coming to market for implementation in HMDs. Table 1 shows a comparison of various miniature display technologies or microdisplays.

The challenge in developing microdisplays for HMDs is providing high resolution on a reasonably sized yet not too large substrate (i.e., ~0.6–1.3 in.), and high uniform luminance, which is measured either in foot-Lambert (fL) or Candelas per square meter (cd/m^2) (i.e., 1 cd/m^2 equals to 0.29 fL). Regarding brightness, some of the most challenging environments are outdoor and surgical environments. In all cases, the brightness of presented images must be at least that of the average environment brightness.[20] The luminance of ambient background for aviators at altitude such as sun-lit snow or clouds may be up to approximately 10,000 fL. The average outdoor scene luminance is typically approximately 2000 fL for mixed scene contents. Thus, a practical aim would be to match 2000 fL. In an open shade, an up to 700 fL display luminance is required, with an average luminance of approximately 150 fL. An alternative to bright microdisplays is to attenuate in part the outdoor scene luminance as has been commonly done in the simulator industry since its inception. Such alternative may not be an option for surgical displays.

Table 1 Microdisplays (<1.5 in. diagonal) for HMDs[a]

	CRT	AM-LCD	FLCOS	OLED	TMOS
Diagonal size (in.)	>0.5	>0.7	>0.6	>0.66	>0.5
Life span (hr)	40,000	20,000–40,000	10,000–15,000	<10,000	>100,000
Brightness (cd/m^2 or Nit)	~100	<100	300–1000	100–700	200–1000
Contrast ratio	300 : 1–700 : 1	150 : 1–450 : 1	up to 2000 : 1	150 : 1–450 : 1	300 : 1–4500 : 1
Type of illumination	Raster scan	Backlight illumination	Illumination optics	Self-emissive	Time multiplex optical shutter
Uniformity	Often brighter in the middle	Often brighter at edges	Depends on illumination	Excellent	Excellent
Pixel response time	Phosphor dependent <1 sec	1–30 ms	1–100 µs	<1 ms	0.1–100 µs
Colors	16.7 M	16.7 M	16.7 M	16.7 M	16.7 M

[a]The table was adapted from Uni-Pixel Displays, Inc. Technology brief (http://www.uni-pixel.com) and China Display Digital Imaging Technology (Shanghai) Co. Ltd. (http://www.hi-definition-television.com/english/tech/cd_compare_en.shtml).

FLCOS displays, which operate in reflection and can be thought of as reflective light modulators, offer bright illumination in telecentric mode (defined later in this entry); however, innovative illumination schemes must be developed to offer compact solutions. OLEDs use polymers that light up when an electrical charge is applied, and thus do not require auxiliary illumination. Such property means that OLEDs will operate under lower power and can be thinner than LCDs. Their brightness can be competitive with FLCOS displays but at the expense of a shorter life span. Another important characteristic often underplayed in microdisplays is the pixel response time, which if slow, can lead to increased latency.[22] In this sense, TMOS display technology may offer competitive solutions. The TMOS technology functions by feeding the three primary colors in rapid alternating succession to a single light-modulating element. Unlike LCD technology that uses color filters, the color is emitted directly from the panel. Opening and closing of the light modulator provide the synchronization that allows the desired amount of each primary color to escape.

Fundamentals of HMD Optics

As we review various HMD optical design forms, we also differentiate between three modes of image presentation, nonpupil and pupil forming, and telecentricity requirements.

Image presentation

Perhaps surprisingly, many deployed VE systems present either monocular or the same images to both eyes. Such systems require neither change in accommodation nor convergence. Accommodation is the act of changing the power of the crystalline lens to bring objects in focus. Convergence is the act of bringing the lines of sight of the eyes inward or outward when viewing near or far objects. In our daily experience, while we gaze at scenes, our eyes focus and converge at the same point. Thus, to avoid side effects, HMD systems need to stay within acceptable limits of accommodation-convergence mismatch. In monocular or biocular HMDs, users accommodate at the location of the optically formed images to obtain the sharpest images. In the case of binocular HMDs, the eyes will converge properly at the 3D location of a 3D object to avoid diplopic (i.e., doubled) vision, while the images will appear blurred if their optical location, which is unique in current HMDs, does not fall within the depth of field of the display optics around the image location.

In practice, driven by far field and near field applications, the unique distance of the optical images can be set either beyond 6 m (i.e., optical infinity), or at about arm length, respectively. Objects within the optics depth of field at a specific setting will be perceived sharply. Other objects will be perceived blurred. For dual near-far field applications, multifocal planes displays are necessary, as discussed later in this entry.

Nonpupil vs. pupil forming systems

Three current basic forms of optical design for HMDs are eyepiece, objective–eyepiece combination, and projection optics. Only the simple eyepiece design is nonpupil forming, because it requires no intermediary image surface conjugate to the microdisplay within the optics. In this case, the eyes' pupils serve as the pupils of the HMD. For each eye of a user, as long as a possible light path exists between any point on the microdisplay and the eye, the user will see the virtual image of that point. An advantage of nonpupil forming systems is the large eye-location volume provided behind the optics. Their main disadvantage is the difficulty in folding the optical path with a beam splitter or a prism without making a significant tradeoff in field of view (FOV). Unfolded optics prohibits see-through capability and balancing the weight of the optics around the head.

Pupil forming systems on the other hand consist of optics with an internal aperture, which is typically conjugated to the eye pupils. A mismatch in conjugates will cause part or the entire virtual image to disappear, and therefore large enough pupils must be designed. The requirements for pupil size should be tightly coupled with the overall weight, ergonomics of the system, field of view, and optomechanical design. Ideally, 15–17 mm pupils are preferred to allow natural eye movement; however, 10 mm pupils have also been designed successfully (e.g., the Army's IHADSS HMD), and as small as 3 mm binoculars are commonly designed.

Telecentricity requirement

Whether in object or image space, telecentric optics operates with a pupil at optical infinity in that space. In the telecentric space, the chief rays (i.e., the rays from any point on the microdisplay that pass through the center of the pupil) are parallel to the optical axis. Telecentricity in microdisplay space may be thought to be desirable to maximize uniform illumination across the visual field; however, it is not necessarily true because many microdisplays exhibit asymmetry off-axis. Telecentricity also further imposes that the lens aperture be at least the same size as the microdisplay, which has to be balanced against the weight constraint. A relaxed telecentric condition is often successfully applied in HMD design.

Human-Visual-System and HMD-Optics Interface

The human-visual system perceives and responds to the images rendered and imaged through the HMD, and therefore its visual and anatomical properties play critical roles in the visual assessment of HMDs. The instantaneous FOV of the human eye is roughly oval and approximately measures 120° vertically and 150° horizontally. Considering the eyes as a pair, the overall FOV measures approximately 120° vertically and 200° horizontally when the eyes are stationary. With eye rotation of nearly ±45°, the overall FOV is about 290° horizontally. Adding head movements, the total visual field extends through almost 360°. The binocular visual field within which an object is visible to both eyes is about 114° when the eyes converge symmetrically and less when they converge on an eccentric point. Thus, HMDs with such FOVs may be desired especially for immersive displays, yet while ideally weighting no more than a pair of eyeglasses. That is the Holy Grail of HMD research.

The initial trend for HMD design was wide FOV optics. Over the years, user acceptance has reversed this initial trend, judging that it is better not to spread the limited number of pixels too thin over a wide FOV, especially for tasks that require resolution close to that of the human-visual system. Microdisplays have advanced significantly in resolution in the last decade. However, even the highest resolution microdisplays will not be satisfactory if the optics magnifies the microdisplay too much to achieve a large FOV. For example, with a 70° FOV and an XGA level of resolution, each pixel subtends about 4 arc minutes. In comparison, the human-visual acuity is lower than 1 arc minute in about a 5° visual region around a fixation point known as the fovea, which equates to resolving approximately 1 mm at a distance of 6 m. Also, the human-visual acuity degrades significantly beyond 10–15° from the fovea. At 10° from the fovea, it is only 20–25% of that at the fovea. The resolution at extreme angles is poor, and the eye is primarily sensitive to image motion. However, because the eyes move naturally within ±20°, we need to have high resolution at least within a 40° FOV, and in practice, unless the resolution can be dynamically addressed based on eye gaze, a uniform resolution is required everywhere the eyes may gaze within the display.

We emphasize that resolution in HMDs is best expressed as the angular subtense of each pixel estimated by dividing the FOV in any direction by the corresponding number of pixels along that direction and converting to minute of arcs (i.e., 1° equal 60 min of arc), rather than by simple pixel count. In the case where the optics is designed to resolve the pixels of the microdisplay, the final image actually appears pixelated. One may choose to design the optics to slightly blur the pixels to remove pixelization as most commonly done, or a micro-optics diffuser sheet may be overlaid on the display surface to blur the edges between pixels.[24] In all cases, resolution should not be set necessarily to match the human-visual acuity but rather to address the needs imposed by specific tasks.

Eye clearance, the point of closest approach of the eye to the HMD, is the most accurate figure of merit used to describe the HMD positioning with respect to the eyes. Viewing comfort for HMDs is believed to depend on adequate eye clearance; hence, the HMD does not touch the eye, brow, or eyeglasses. The alternative to providing adequate eye clearance is to provide refractive correction for each user, either as a focus adjustment or as an optical insert. The absolutely smallest value of eye clearance allowable for the wear of standard eyeglasses is 17 mm, which corresponds to 15 mm from the eye to the inner surface of the eyelens, and 2 mm glass thickness. While 23 mm eye clearance is recommended to accommodate most eyeglasses, values may vary depending on the application and user population. The eye relief indicates the distance from the center of the last surface of the optical system to the expected location of the eye and is most often provided instead of the eye clearance. Large values of eye relief do not necessarily provide sufficient clearance.

It is usually a challenge to design an optical system that allows adequate eye clearance as well as a large pupil size. The larger the microdisplay, the larger the eye clearance. A main limitation of eyepiece-based HMD design is the fact that an increase in eye clearance requires larger viewing optics for a given FOV as shown in Fig. 1, thus yielding a loss in compactness, increased weight, and a degradation of optical performance because more of the outer periphery of the lenses is considered as we increase eye relief. In the case of projection optics, the pupils (i.e., entrance and exit pupils) are located within the optics (an example of projection optics design is shown in Fig. 6 where the pupil is located between the ''DOE lens'' and the ''ASP lens''), and to ensure low distortion the pupils can be assumed to be located at the nodal points of the optics. However, if the eye is not conjugated to the pupil of the optics, the user will experience extensive vignetting (i.e., light loss from regions of the image). Thus by design, one expects that the beamsplitter will be positioned so that the user's pupil will be comfortably conjugated to the pupil of the optics via

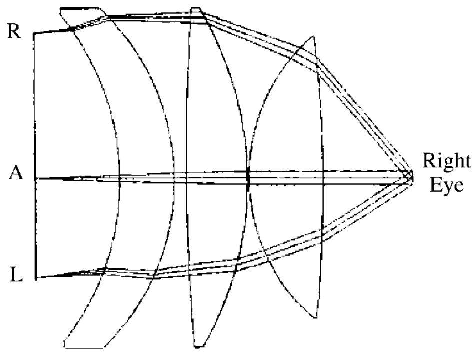


Fig. 1 LEEP optics. Courtesy of Eric Howlett for providing the optical layout.

the beamsplitter. Importantly, vignetting can also be used on purpose to reduce the size of lenses and therefore reduce weight.

The pupil diameter of the eyes ranges from about 2–8 mm according to the level of environment lighting. In principle, under the highest level of illumination, smaller HMD exit pupils may be sufficient. Such observation is only useful in low-vibration environments. In all cases, unless the HMD is equipped with eye-tracking capability, the exit pupil of the HMD should be larger than the effective pupil of the eye to allow for natural eye movements. Importantly, the size of the pupil will set the FOV vignetting when natural eye movements occur. A minimum pupil size may be computed based on the fact that eye movements occur within $\pm 20°$, with 90% of all eye movements occurring within $\pm 15°$. Finally, visual performance should be assessed for various decenters of the smaller pupil of the user within the pupil of the HMD to account for actual use of the instrument, even for systems with IPD adjustments.[25]

The match between a user's IPD and the optical separation between the left and the right eye in a binocular HMD is also critical to visual comfort. A variation in IPDs ranging from 55–75 mm includes the 95 percentile of values across White, Black, and Asian populations combined. A mean value of 64 or 65 mm is often considered in engineering investigations. If a user's IPD is significantly different from that of the HMD, increased fusional difficulty and discomfort may occur to the observer, especially in the case where the user's IPD is smaller than the HMD setting. In such extreme mismatch, headaches and nausea may even occur. In the reverse case where the user IPD is larger than the setting, erroneous depth perception will occur because a user's IPD sets the scale for depth perception.

In the case of binocular displays, depth discrimination or stereoacuity threshold is important and may be expressed angularly as $\eta(\mathrm{rad}) = \mathrm{IPD} \cdot \delta D / D^2$ where δD is the depth difference between two points, and D is the user viewing distance.[26] The stereoacuity threshold varies widely among users between about 2 and 130 sec of arc. A typical value may be chosen to be 30 sec of arc. Other factors that may cause various levels of discomfort are eye divergence of even a few degrees (i.e., the act of bringing simultaneously the lines of sight outwards beyond the straight ahead viewing direction to fuse the two virtual images) or dipvergence up to 5–10 min of arc for immersive HMDs and 1–3 min of arc for see-through designs (i.e., the act of forcing the eyes to move at different elevations) to fuse the images. Excessive values for divergence of dipvergence may prevent the user from fusing the images.

Finally, in any optical design, including HMDs, optical aberrations will degrade image quality in two possible manners: blur and warping. Blur of the image may be caused by combinations of axial chromatic, spherical aberration, coma, astigmatism, and field curvature. Warping of the image may be caused by distortion and lateral chromatic aberrations. However, coma also provides a displacement of the chief ray with respect to the centroid of energy emanating from a point in the FOV, and thus also induces small amounts of warping.[27] In designing and assessing HMDs, it is critical for the designer to relate image quality performance to image quality in visual space in order to provide users across multiple disciplines access to such information.[28]

HMD OPTICS

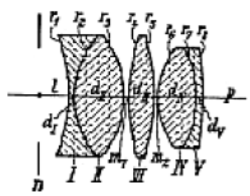
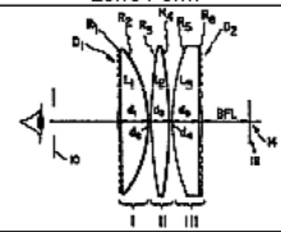
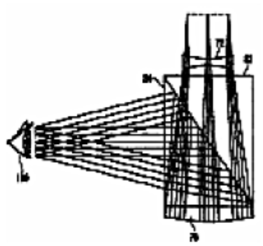
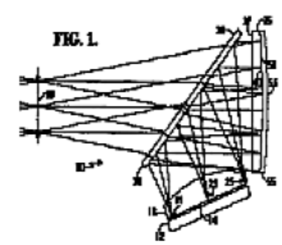
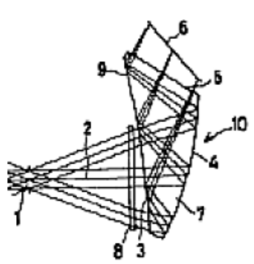
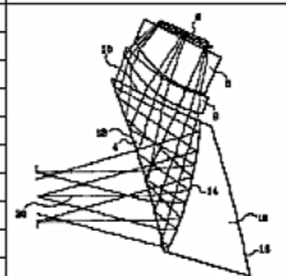
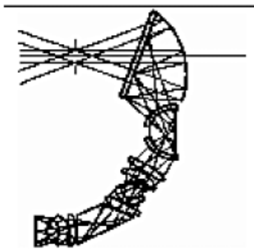
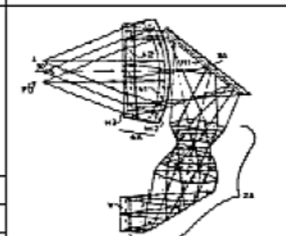
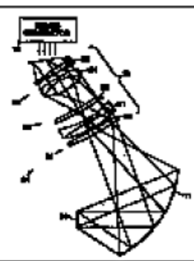
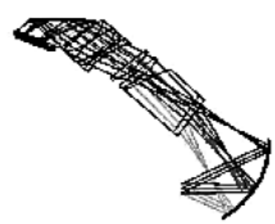
Immersive vs. See-Through Designs

HMD designs may be classified as immersive or see-through. While immersive optics refer to designs that block the direct real-world view, see-through optics refer to designs that allow augmentation of synthetic images onto the real world.[29] Whether immersive or see-through, the optical path may or may not be folded. Ideally, immersive HMDs target to match the image characteristics of the human-visual system. Because it is extremely challenging to design immersive displays to match both the FOV and the visual acuity of human eyes, tradeoffs are often made.

The LEEP optics shown in Fig. 1 was the first large FOV nonpupil forming optics extensively used in the pioneering times of VEs.[30] The optics used a non-folded design type. The classical Erfle eyepiece[31] as well as other eyepiece designs are shown in the first three rows of Table 2.

See-through designs more often follow a folded design, particularly optical see-through displays. In such displays, the optical combiner is a key component

Table 2 Examples of key HMD optics design forms

Picture	Specification	Lens Form	Specification
	FOV 70 ELF 100 *H. Erfle* 1478704		FOV 70 EFL 100 *Michael D. Missig* 5446588
	FOV33 EFL 34 *J. D. Robinson* *C. M. Schor* *P.H. Muller* *W.A. Yankee* eyepiece 5696521		*B.S. Fritz* HMD using Mangin Mirror combiner 5838490
	FOV40-60 EFL 100 Takayoshi Togino Eyepicece with DOE 6181475 5959780		FOV 40 15.2x12.3 MicroDisplay F#/1.7 *J.G. Droessler* Honeywell,Inc Morristown, NJ 6147807
	FOV 50x60 *J.G. Droessler* *D.J. Rotier* Tilted Cat Ocular 1989		FOV 120 *C. Antier* *Jean-Blaise Migozzi* Holographic Binocular Helmet Visor 5124821
	FOV50x60 color Helmet visor display *B. Chen* Off-axis Design 5526183		FOV 60 color 1.3" diagonal CRT *J.P. Rolland* Off-axis Design *IODC94; OE 2000*

in distinguishing designs. In folded designs, the center of mass can be moved more easily back. Folded designs, however, often indicate optical system complexity. A large majority of folded designs use a dual combiner, where reflections off a flat plate and a spherical mirror combined are used as shown in the second row of Table 2. Droessler and Rotier[32] used a combination of dual combiner and off-axis optics in the tilted cat combiner. In Antier and Migozzi,[33] various key HMD components were assembled, including a pancake window element close to the eye enabling a wide FOV eyepiece.[34] The drawback of pancake windows has been their low transmittance of approximately 1–2%; however, recent advances yield pancake windows with up to 20% transmittance.[35] Finally, off-axis optics designs with toroidal combiners have also been designed; two examples are shown in the last row of Table 2.[36,37] The use of a toroid combiner serves to minimize the large amount of astigmatism introduced when tilting a spherical mirror.

Balancing Field of View and Resolution

Three main approaches have been investigated to increase FOV while maintaining high resolution: high-resolution insets, partial binocular overlap, and tiling.[38]

High-Resolution Insets

Given the property of the human-visual system to have high visual acuity only over a narrow region around the fovea, a small area of high resolution, referred to as an inset, can be superimposed on a scene or on a large low-resolution background to virtually create an apparent large FOV with a high-resolution inset as shown in Fig. 2. In such systems, the position of the inset may be dynamically controlled by the gaze point as in the CAE Fiber Optic HMD shown in Fig. 3 (FOHMD),[39] or different images may be presented to the eyes as in dichoptic area of interest displays.[40] The FOHMD provided a binocular horizontal FOV of 127° with about 38° overlap, and a 55° vertical FOV. The display angular resolution was about 4 arc minute/pixel. It provided a brightness of 30 fL and a contrast of 50 : 1. These systems provided significant improvements over ordinary displays and were considered the best displays available, in spite of the fact that they were heavy and extremely expensive. The main drawback was the reduced mobility.

Also, Iwamoto et al.[41] used 2D optomechanical scanners to register a high-resolution inset, controlled by the gaze point, with a wide FOV low-resolution background image. A low-cost high-performance inset HMD system that uses fully optoelectronic components instead of moving mechanical parts was conceived and illustrated in Fig. 4.[42] The use of fixed optoelectronic components allows the whole system to be fabricated with fewer alignment errors, to be immune to mechanical failure and, in general, to be more tolerant to vibrations. The basic concept of the optoelectronic high-resolution inset HMD is to optically duplicate the inset image using microlenset arrays,[43] and to select one copy by blocking the other copies using liquid crystal shutters. The selected copy of the inset image was then optically superimposed on the background image. The inset image traces the gaze point; thus, the user sees the whole field at high resolution.

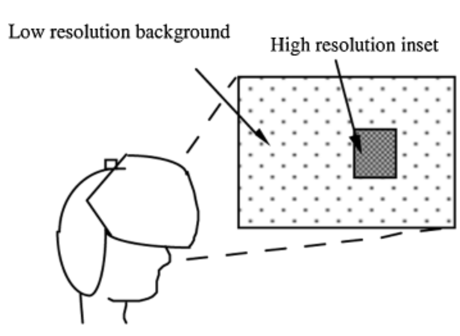


Fig. 2 Schematic of a high-resolution inset.

Fig. 3 Fiber optics HMD. Courtesy of CAE electronics. *(View this art in color at www.dekker.com.)*

Partial Binocular Overlap

Partial binocular overlap is created by tilting the optical axes of the optics for each eye outwards in order to increase the binocular horizontal FOV at the expanse of the FOV overlap between the two eyes. An unresolved question is what amount of overlap would be appropriate for a given FOV. Grigsby and Tsou have argued for a binocular overlap of at least 40° based on visual considerations,[44] while studies at Kaiser Electro-Optics indicate a user preference for partial overlap as a percentage of the overall binocular FOV.[38] Based on research reported, the required

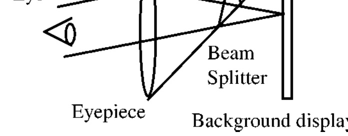


Fig. 4 Schematic of a high-resolution inset with no moving parts and sub-inset resolution.

binocular overlap likely depends on the specific tasks to be performed.

Tiling

Tiling consists in arranging small FOV displays in a mosaic to create a wide FOV system. Tiling may be done mechanically or optically. Both approaches lead to complexity, bulkiness, and increased cost; however, higher resolution may be reached compared to single microdisplay per eye systems. Challenges associated with tiling include the alignment of the tiles and the minimization of the seams between the tiles.

Achieving High-Brightness Displays

Alternatives to microdisplays are laser or laser diode-based scanning displays, which offer brighter displays and target applications in the outdoor and medical domains. A recent approach is the virtual retinal display (VRD), also called the retinal scanning display (RSD).[45] The RSD was first demonstrated by Tom Furness and his colleagues at the HIT Laboratory in the University of Washington. In such systems, the pupil of the eyes is optically conjugated to the microscanner exit pupil. As such, a challenge revealed early in the development of the technology was the small exit pupil (i.e., 1–3 mm) within which the eyes need to be located to see the image, which can be overcome by forming an intermediary image followed by a pupil expander. Many devices have used a projection device, a screen, and an eyepiece magnifier to expand the viewing volume. The NASA shuttle mission simulator (SMS) rear window is a prime example of the technology. Controlled angle diffusers have been designed for pupil expansion in HMDs, including diffractive exit-pupil expanders.[46] Given an intermediary image, the VRD also functions with an equivalent microdisplay, in this case formed using scanned laser light. Thus, optically, the VRD closely approaches other HMD technologies.

A recent technology based on scanned laser light is the optical CRT.[47] In this approach, a single infrared laser diode is used and scanned across a polymer thin plate doped with microcrystals. Optical upconversion is used to have the microcrystal emit light in the red, green, and blue regions of the spectrum. Such technologies build from the pioneering work of Nicolaas Bloembergen.[48] The advantage of using a laser diode as opposed to a laser is the suppression of speckle noise.

Advances in Optical Design Forms

The optical power is defined as the inverse of the focal length. Regardless of the optical imaging approach, the smaller the size of the microdisplay, the higher the required power of the optics to achieve a given FOV, given that their product yields the FOV. Also, the higher the optical power, the larger the number of optical elements required to achieve a given image quality. Finally, given an FOV and resolution, the smaller the microdisplay size, the smaller the pixel size.

Overall advances in optical design for HMDs capitalize on emerging technologies that are becoming more readily available such as aspheric surfaces, diffractive optics, and plastic lenses. Aspheric surfaces are known to control lens aberrations and to help reduce the number of elements necessary to achieve an overall optical performance. For example, Daeyang's Cy-visor adopted free-form lenses to minimize the weight of the optical system and improve image quality as shown in Table 3. Diffractive optical elements (DOEs), which are known to have negative chromatic dispersion and thus can be used to correct the chromatic dispersion of positive lenses, have also begun to play an important role in HMD designs.[49] Plastic components are known to possess the advantages of low cost and weight.

RECENT ADVANCES AND PERSPECTIVES

Because of their broad application domains, HMDs must be designed and targeted at key applications and task specification, and must be tested with the targeted end users for advanced tasks. Beside military applications that dominated the market of HMDs for several decades, more recent applications include medical, user interface design, visual aid for everyday life, manufacturing, and distributed collaborative environments. Driven by the limitations of existing HMDs, we now discuss the development of head-mounted projection displays (HMPDs), and the prospective designs of eye-tracking integrated HMDs, multifocal planes HMDs, and occlusion displays.

Head-Mounted Projection Displays

A shift in paradigm in HMD design is the replacement of compound eyepieces with projection optics combined with phase conjugate material (e.g., retroreflective optical material), known as head-mounted projection displays.[49,50] As illustrated in Fig. 5A–B, an HMPD consists of a pair of miniature projection lenses, beam splitters, and microdisplays mounted on the head and a supple and nondistorting retroreflective sheeting material placed strategically in the environment. Fig. 5C shows a deployable room coated with retroreflective material known as the Artificial Reality Center (ARC).[13] Other implementations of

Table 3 Major commercial HMDs

Vendor	Model	Microdisplay type	Presentation mode	See-through	FOV (deg)	Resolution (arcmin)	Weight (g)
Daeyang E&C	Cy-visor DH4400VP-3D	LCOS, color	Binocular	No	25(H) 18.9(V)	1.875 (800 × 3) × 600	~160 g
Daeyang E&C	Cy-visor DH-4500VP	LCOS, color	Biocular	No	25.8(H) 19.5(V)	1.935 (800 × 3) × 600	~160 g
I-O Display Systems	i-O glasses SVGA 3D	LCOS color	Binocular	No	20.9(H) 15.8(V)	1.57 (800 × 3) × 600	~200 g
Kaiser-Electro-Optics	ProView XL35	AMLCD, color	Binocular	No	28(H) 21(V)	1.6 (1024 × 3) × 768	~993 g
Kaiser Electro-Optics	ProView XL50	AMLCD, color	Binocular	No	40(H) 30(V)	2.3 (1024 × 3) × 768	~993 g
Kaiser Electro-Optics	ProView XL50 STM	AMLCD, green	Binocular	Yes	47(H) 26(V)	2.75 1024 × 768	~795 g
Microvision	NOMAD	Retina scanred	Monocular	Yes	23(H) 17.25(V)	1.725 800 × 600	~227 g
Micro Optical	SV-6 PC viewer	color	Monocular	Yes	16(H) 12(V)	1.5 640 × 480	~35 g
N-vision Inc.	DataVisor	Mono CRTs	Binocular	Yes	42.6(H) 32.6(V)	1.9 1280 × 1024	~1589 g
NVIS Inc.	nVisor SX HMD	FLCOS	Binocular	No	49.6(H) 38.2(V)	2.2 (1280 × 3) × 1024	~1000 g
SONY	Glasstron PLM A55	LCD, color	Biocular	Yes	24(H) 18(V)	5.4 800 × 225	~150 g
SONY	Glasstron PLM-700	LCD, color	Biocular	Yes	30(H) 22.5(V)	2.2 (832 × 3) × 624	~120 g
Trivisio	3SCOPE Goggles	LCD, color	Binocular	No	32(H) 24(V)	2.4 (800 × 3)×600	~120 g
Trivisio	ARvision-3D HMD	LCD, color	Binocular	Yes(video)	32(H) 24(V)	2.4 (800 × 3)×600	~230 g
Virtual research	V8	AMLCD, color	Binocular	No	49.6(H) 38.2(V)	4.65 (640 × 3)×480	~965 g

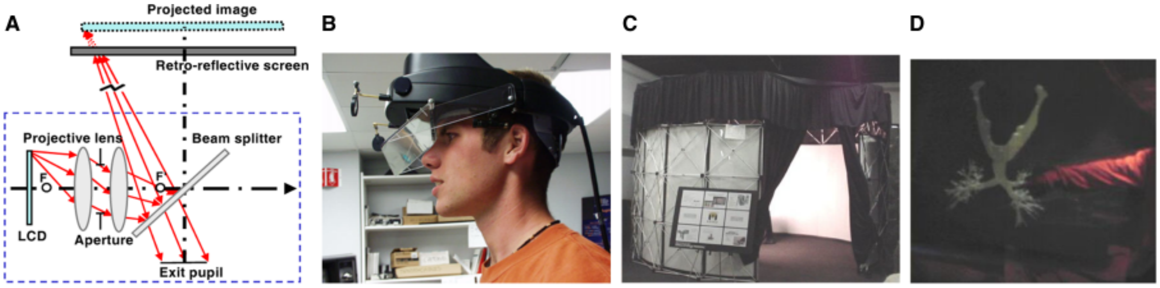


Fig. 5 HMPD in use in a deployable Augmented Reality Center (ARC): (A) Schematic of the HMPD optics; (B) user wearing a HMPD; (C) the ARC; and (D) user interacting with 3D models in the ARC. *(View this art in color at www.dekker.com.)*

retroreflective rooms have been developed.[51] An image on the microdisplay, located beyond the focal point of the lens, is projected through the lens and retroreflected back to the exit pupil, where the eye can observe the projected image as shown in Fig. 5D.

Projection optics, as opposed to eyepiece optics, and a retroreflective screen, instead of a diffusing screen, respectively, distinguish the HMPD technology from conventional HMDs and stereoscopic projection systems. Given a FOV, projection optics can be more easily corrected for optical aberrations, including distortion, and does not scale with increased FOV, given the internal pupil to the lens, which is nevertheless reimaged at the eye via the beamsplitter oriented at 90° from that used in conventional eyepiece folded optics. The optical designs of a 52° and 70° FOV projection optics are shown in Fig. 6A and C, respectively.[17] The steady progress of HMPD engineering is provided in Fig. 7. In Fig. 7B, the HMPD prototype is augmented by infrared markers for conformal tracking, yielding approximately 0.03° in tracking accuracy for orientation left to right, 0.1° up and down, and 0.1 mm for position.[52] Not shown is the recent development of an HMPD with retroreflective material directly integrated within the HMD to allow its use in outdoor environments.[53]

Eye-Tracking Integrated HMDs

The interaction capability currently integrated into HMDs is typically limited to the use of head and hand trackers. For situations that require fast response time or difficult coordinated skills, eye movement can be used in conjunction with those trackers to provide effective, fast, and flexible interaction methods. Since early implementations of eye-slaved flight simulators, tremendous interest in gaze–contingent interface techniques has endured and permeated several disciplines including human computer interfaces, teleoperation environments, and visual communication modalities. Such permeation may be explained by the important role that eye tracking may also play as a measuring tool for quantifying human behavior and states of awareness in VEs, in providing more accurate depth perception,[54] and positioning a high-resolution inset at the user's eye gaze as discussed earlier in this entry.

Optical layouts of eyetracking integration have been proposed.[55] Depending on the configuration of the infrared illuminator, on-axis illumination leads to bright pupil tracking, while off-axis illumination shown in Fig. 8 leads to dark pupil tracking. When combined with corneal reflection tracking, relatively accurate tracking may be achieved. In

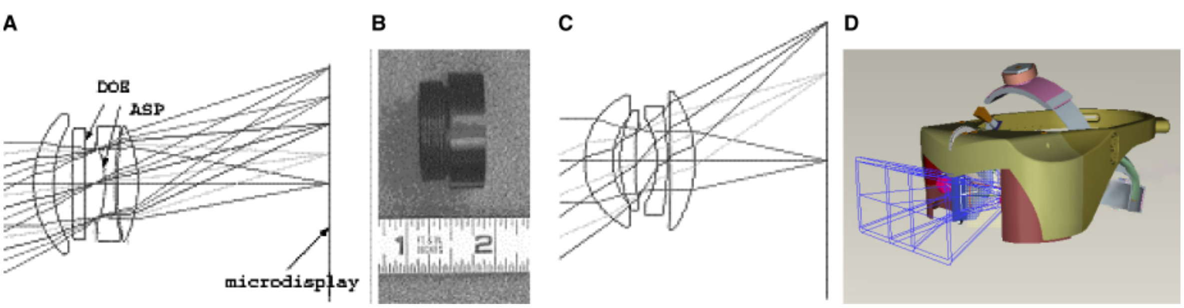


Fig. 6 (A) Optical layout of the 52° FOV ultra-light projection lens showing the diffractive optical element (DOE) surface and the aspheric surface (ASP); (B) the 52° optical lens assembly and size; (C) optical layout of the 70° FOV ultra-light projection lens; (D) side mounted optics HMPD.*(View this art in color at www.dekker.com.)*

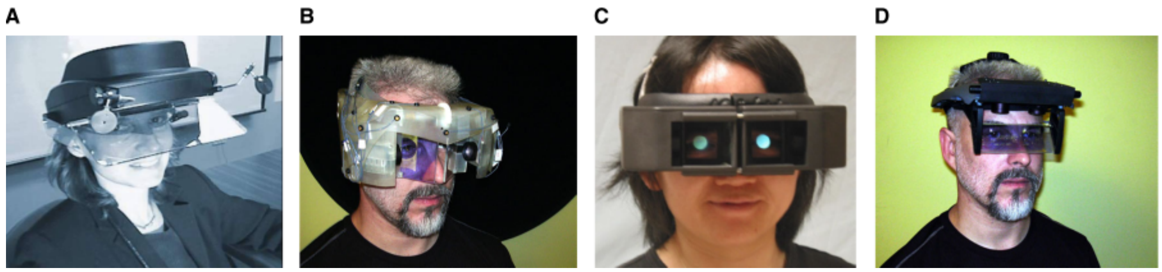


Fig. 7 Steady progress in engineering HMPDs. These systems are prototypes and the overall HMD weight varies based on the use of metallic structures (D) and heavy fast prototyping resins (A–B) as opposed to only plastics (C). The weights of the optics are about the same across all the prototypes shown and about 6 g per eye. *(View this art in color at www.dekker.com.)*

HMD–eyetracker integration, the helmet may slip on the head as a consequence of the weight of the HMD, which may be confused with eye movement. A viable approach to compensate for the slippage of the HMD on the head is to detect the motion of the helmet with respect to the eye or the head itself. Another approach is to simultaneously track two features of the eye that move differentially to distinguish helmet slippery from eye movements. Much research is required not only to optimize the design and performance of eyetracker–HMDs, but also to assess human-in-the-loop performance across various tasks.

Multifocal Plane Displays and Occlusion Displays

While the pursuit of higher resolution and ergonomic designs will provide working solutions to a subset of specific applications, even the highest resolution devices will not provide 3D perception as available in the real world until they provide realistic accommodation and occlusion cues.

While accommodation is a weak cue in itself for the perception of depth compared to other cues (e.g., occlusion, head motion parallax, stereopsis), when we look around in the real world, the whole world is not all in focus at once. In fact, as we move our gaze from the far field to examine a nearby object, there is a delay as we bring our visual apparatus into optimum adjustment. This delay is due to the time required to accommodate the lens in each eye (i.e., 0.3 sec delay and up to 0.9 sec for a 2 diopters range) and to converge the two eyes to gaze at a given point on the object (i.e., 10° per sec).[56] During the delay, our eyes are not properly adjusted and this out-of-adjustment viewing is a routine part of our everyday visual experience. A lack of convergence in an HMD, however, may lead to diplopic vision for near field objects, which in some cases and for certain tasks could be compensated for with the image generator. However, any compensation must be well understood to assess the impact on perception. Under proper vergence of the eyes in space, induced accommodation will follow away from the plane of the displayed virtual images, which will then be perceived blurred if the user is accommodated outside the corresponding depth of field around the virtual image.

To provide proper accommodation in HMDs, it has been suggested to vary the focal depth either by using an oscillating lens or by adjusting the image depth based on the user's gaze point.[57] Other solutions have

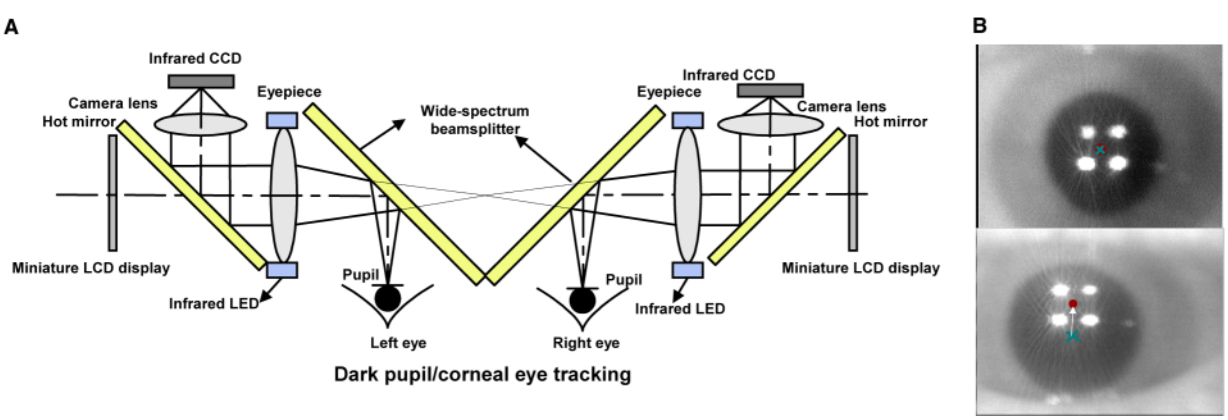


Fig. 8 Schematic illustration of eyetracking integration in HMDs. *(View this art in color at www.dekker.com.)*

also been outlined. An imaging system that included a foreground plane and a background plane was also investigated.[58] A volumetric projection display was proposed, whose concept was applied to HMDs.[59]

Mutual occlusion is an attribute of see-through displays where real objects can occlude virtual objects and virtual objects can occlude real objects. To have virtual objects occluding the real environment, we need some means of blocking the light. Sutherland concludes in his 1968 paper that "showing "opaque" objects with hidden lines removed is beyond [their] present capability."[1] It is well established that any beamsplitter will reflect some percentage of the incoming light and transmit the rest. This transmitted light implies that with only a beamsplitter and a single image source-based display, it is optically impossible to overlay opaque objects. The second component for mutual occlusion, the requirement to have real objects blocking the virtual objects, requires a mechanism for sensing depth. Existing propositions and prototypes for occlusion displays have been developed.[60,61]

CONCLUSIONS

While since the 1960s military simulators have driven HMD designs with key tasks in far field visualization with collimated optics, many other applications from medical to education have emerged that are driving new concepts for HMDs across multiple tasks up to near field visualization. Today, no HMD allows coupling of eye accommodation and convergence as one may experience in the real world; yet only few HMDs provide either high resolution or large FOVs, and no HMD allows correct occlusion of real and virtual objects. HMD design is extremely challenging because of Mother Nature who gave us such powerful vision in the real world on such a complex, yet small network called our brains. New constructs and emerging technologies allow us to design yet more and more advanced HMDs year by year. It is only a beginning. An exciting era of new technologies is about to emerge driven by mobile wearable displays as it applies to our daily lives in the same way portable phones are glued to the ears of billions of people, as well as to high tech applications such as medical, deployable military systems, and distributed training and education.

ACKNOWLEDGMENTS

We thank James Melzer for his review and suggestions about this entry, Yonggang Ha for his assistance with sections of this manuscript, and Ozan Cakmakci and Cali Fidopiastis for stimulating discussions. We are indebted to the National Science Foundation for their continued support through grants IIS/ITR00-82016, IIS/ITR 00-83037/03-01874, EIA 99-86051, IIS/HCI 03-07189, and IIS/HCI 03-07227/04-11578, the Office of Naval Research through grants N00014-02-1-0261, N00014-02-1-0927, and N00014-03-1-0677. Finally, we thank the U.S. ARMY STRICOM for their continued support.

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