Perception in HMDs

What is it in Head Mounted Displays (HMDs) that really make them all so terrible?

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ABSTRACT

Head mounted displays (HMDs) have disappointed real world users in their inability to live up to over-hyped expectations. This does not, however, mean that HMDs are useless. While still technologically lacking in some areas, appropriately designed HMDs can be extremely useful tools. We will look at the limitations of current HMDs and ways around them. Rather than approach the problem from the optical, electrical and mechanical engineer's point of view, we will approach it from the physiology point of view, answering the question; what is needed to create a useful HMD?

The paper is divided into two separate sections. The first, is a description of the performance of the human visual system. The second, addresses how designers attempt to mimic the human visual system in an HMD. This second section will discuss applications that need the specific performances described in section one, current solutions to those needs and finally ideal solutions not yet implemented. Finally, a summary of these findings is presented in a table format.

PERFORMANCE OF VISUAL SYSTEM

I. Field of View

Each eye can see 140° horizontally and 110° vertically. Most viewing is looking strait ahead and when combining the two eyes as a team, as most of us do, the horizontal FOV is about 195°. A landscape image is the result of these combined images and displays, TV, HMDs exploit this comfortable format. However, when an HMD is used in a walking or mobile situation, the rules change.

For balance, the wearer needs a horizon. Outside, vanishing points are a necessary. While indoors, a floor edge must be visible. The indoor HMDs requires a large FOV since a distance of 2 meters from a wall requires a downward visibly of about 45°. A smaller FOV is acceptable in many stationary uses; however, in mobile or walkthrough situations, very large FOV is critical. A minimally acceptable 60° vertical FOV and minimum 75° horizontal is required for mobile uses.

II. Resolution

The eyes tend to work hard to focus a blurry or low-resolution image. When the image displayed is of low quality, out of focus or too few pixels, the eye strains and becomes tired. FOV does not contribute to this.

In the center of the eye, the maximum discernible resolution is 1 arcsec. However, 1 arcmin is completely acceptable for long term use and 3 arcmin is acceptable for shorter wear times. During times of moderate movement, 2-4°/ second, resolution can be decreased about ½ in the direction of rotation without adversely affecting the HMDs wearers viewing quality. What this saves the designer is not as much in the HMD itself but in the video image creation of having to calculate or render fewer pixels.

III. Color Resolution

There are no HMD displays capable of displaying accurately the entire sensitivity range of the eye. However, this should not be considered a technological hindrance. The interest in most HMDs is displaying daylight (photopic) imagery, preferably in color. Some military and surveillance users require low, monochrome light levels to maintain night vision (scotopic) capability.

The eye, in the photopic sensitivity region, can see an intensity variation of about 1000 to one for each of the three colors; Red, Green, and Blue. This translates to 10 bits per color or about 30 bits color depth for each pixel resolvable by the eye. Not all applications require such depth and this should be noted during design and purchase of an HMD.

A unique aspect of this color depth is that it is not needed throughout the viewing area. In fact, as viewing angles extend beyond 60°, many colors can no longer be detected. As an experimental verification, while looking strait ahead, close the left eye, and pass two pens, one blue and one green, from the leftmost view point to straight ahead. Both pens appear to be gray at first. As they move closer toward the center of the FOV, the color in the blue pen becomes apparent before that in the green pen. When passing the pens back the other way, the colors will stay with them the whole way. This is because the brain has associated color to that object. Figure 1 shows the color sensitivity from the nasal out to the temporal FOV.

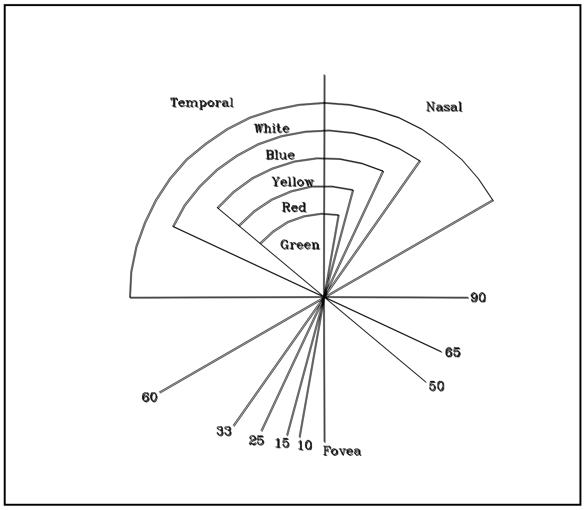

Figure 1 Angular color visibility

This realization in perception may help designers of HMDs to reduce the information level in these areas without adversely affecting the wearer.

IV. Accommodation/Stereo

The visual cues pertaining to depth perception include occlusion, stereo, accommodation, and vergence. Of these, occlusion, closer objects blocking more distant objects, is the most important. Occlusion is the only depth cue for objects beyond 2 -3 m from the observer and is extremely important when objects, or the user, are in motion. Stereo, a different view seen by the left and right eyes, becomes the next most important cue for objects closer than 3 m. Depth through stereo can be achieved without accommodation as is the case in most HMDs and without vergence as with autostereograms. Both of these prove unsatisfactory for extended use applications because of eye fatigue.

Accommodation, changing the focus of the eye for objects of varying distances, is very important for the long-term comfort of the HMD user. On average, a person changes focus several times each minute. Each re-focus exercises the eye muscles. The fatigue reported by people who stare into computer monitors all day is partially caused by keeping a fixed focus for longer than is natural. Vergence, aiming the pupils directly at an object, is not a critical cue for depth perception, but it is used for objects closer than 1 m. Discomfort occurs when the stereo cue places an object in a different location than either (or both) the accommodation or vergence cues.

If an image is to look and feel real, it must contain all four depth cues. Emphasis toward each of these depth cues in an HMD design depends on application and length of time the wearer will be using the HMD.

V. Eye Characteristics

The physical characteristics of the eye strongly affect the performance of the human visual system. Pupil characteristics are the most relevant to HMD designs. HMDs must account for both the size and location of the pupil of the eye. The pupil can vary in diameter from 2 mm in bright light to 7 mm in darkness. Under normal daytime indoor conditions, 4 mm is a good average pupil diameter to use in HMD design. The pupil, however, is not stationary. The eye rotates about a point roughly 12 mm behind the pupil. Easy rotation angles are ± 7.5° (H) and + 0°, - 30° (V) while maximum rotation angles are ± 15° (H) and + 30°, - 35° (V). Accounting for a 4 mm pupil diameter and easy eye motion means that HMD designs have to have an exit pupil located at the eye pupil which is roughly ± 5 mm (H) and + 3 mm, - 9 mm (V).

VI. Head Motion

The head motion that an HMD will encounter depends highly on the application. Typical vertical motion is but ± 15° sitting and ±10° standing[1]. Comfortable horizontal movement is ±45° easy and ±79° maximum and the rotational speed can be greater than 500°/ sec. However, a heavy HMD will slow this rate down. Additionally, a heavy HMD also decreases the total vertical motion. This is due to the unnatural balancing of several pounds on one's head. People accustomed to HMD use will normally utilize a full motion pattern.

Head motion for medical use will exceed the standard vertical range by looking downward at a 45° angle for extended periods. Military pilots also extend the standard head motions required including rotational speeds.

Tracking is extremely important for head motion. Lag between the image displayed and the actual head orientation/location can be the greatest obstacle in creating an effective HMD based system. The motions expected in the HMD should be the basis for determining what type of tracker will be needed. When an image registered see-through type display is needed or targeting is desired, lag must be minimized to ≤ 16ms. Although a lag of 16 ms is perceivable, most HMD / tracking / rendering systems are in the 60 – 90ms range.

MIMICKING HUMAN VISION IN HMDS

I. Wide FOV

Wide Field of View displays are needed in walk-through systems, pilot HMDs, and games. These are all applications where data is gathered from the periphery, adding a sense of "presence". WFOV displays require large eye movements, which necessitates large exit pupils for the optics.

Most HMDs that advertise WFOV are actually around 60°. This is due to that it is optically difficult to create a wrap around image from a single display device in a severely restrictive volume as an HMD. The exit pupil is too great while the F #s are too small.

Figure 2 Wide FOV HMD

[1] Woodson

To work around these problems, one particular solution uses multiple displays with separate optics that wrap around the eye. This tiled system is designed by Kaiser Electro Optics (Figure 2). It has 6 color displays per eye providing a FOV of 150^o horizontal and 50^o vertical with a 40^o overlap[2]. However, its 1.5 lb. weight and complicated mechanism required to maintain the display's position for the user make it appropriate only for laboratory use. Additionally the display has scene breaks, or mullions, between displays. While mullions are actually preferable to edge blending (even slight errors are unacceptable), this system has mullions located directly in the center of the FOV. This is annoying and unacceptable.

An ideal WFOV display would have variable resolution. Putting a very high concentration of pixels directly in front of each eye and digressing as one goes towards the edges. A full periphery display, all 195^o would be extremely useful in walk-through type applications. Projection systems are able to provide the WFOV immersion better than HMD historically

II. Resolution

Surgery, inspection and mobile data are all applications that are more effective in sacrificing WFOV for the same pixels in a high resolution, medium to narrow FOV display. These are also applications where long user wearer times are important. Weight of the display is critical.

Many narrow FOV HMD systems are available commercially with all varieties of resolutions. This is mostly limited by the pixel count of the displays available. To increase resolution beyond single displays, frame sequential color and tiled displays are used; both with their own drawbacks. Additionally there is a tradeoff between high resolution and weight. Currently, the highest resolution displays are field sequential CRTs updating at 180hz with over 1000 lines resolution. There are some experimental flat displays, LCDs, Ferro-electrics, etc.., which can match this resolution but none are commercially available.

Optimally, one would want a resolution of 3 arcmin across the entire FOV and no discernible pixels. Scanning type displays can offer the highest resolution but tend to be too bulky for HMD use. Reflective LC type displays (ie. FLCs) appear to offer hope for the smallest and lightest HMD solution.

III. Color Depth

High color depth (24 bit) is very useful in surgery HMD applications where subtle shading provides information on tissue types and shapes. In other applications, 16 bit color is more than adequate. For mobile information displays, 8 bit monochrome display may be acceptable.

Currently, the best color HMDs have three channels red, green and blue. These are combined into s single display providing 24 bit color but they are bulky in size and weight. Frame sequential color schemes provide the next best, and perhaps most promising, color displays. By cycling through each of the 3 colors at 180 Hz, the resultant color display operates at 60 Hz. Displays that operate in this manner include CRTs, Digital Micromirror Displays (DMD) and reflective LCDs. Current ferrroelectric liquid crystal (FLC) displays are capable of 15 bit color and are expected to reach 24 bit color by 1999. Standard transmissive LCDs can provide 24 bit color in a single display but require 3 pixel triads. This reduces the effective resolution of the display.

Some people are bothered by 60 Hz frame sequential color because of the beating which occurs between the integration time of the eye and the color cycling. The result is described as color "tearing". Ideally, all three colors would be cycled through at faster than 60 Hz to minimize this effect.

IV. Accommodation/Stereo

Accommodation and stereo features in an HMD are most necessary in relatively close detailed work as well as long usage time applications. Remote manipulation (ie. assembly) requires the added depth cue of stereo for

[2] Kaiser Electroptics and UNC HMD

precise motions. HMD-based surgery not only needs stereo for detailed work but often last for several hours requiring accommodation and vergence for user comfort.

Occlusion calculations can be taken care of at the image generation computer when the user is fully immersed in the HMD. However, in video see-through and especially optical see-through, the problem exists of matching/superimposing computer generated data with the real world scene. In optical see-through, the superimposing of information and registration to a zero time lag, real image is extremely difficult. Because of the high accuracy registration requirement, tracking for optical see-through systems must be absolutely (globally) accurate to the resolution of the displays. This is very taxing on most tracking methods.

Figure 3 Video see-through

Video see-through does not require the absolute registration that optical see-through does. The real world scene is presented as a video image therefore occlusion is determined digitally before the image is displayed. A video see-through system is shown in Figure 3 being worn by a surgeon during a practice breast biopsy. This unit was custom designed by UNC and the University of Utah. It contains a UNC patented compact display system and miniature color CCD cameras. The two folding mirrors image the camera apertures at the pupils of the user's eyes. This co-locating removes any parallax errors between the camera FOV and that of the eye, creating a correct depth image for the wearer. This is very important for surgical use.   The white cable is the receiver for the tracker system.

Current HMD systems offer stereo and, by way of a overlap in the FOV, they offer some degree of vergence. Accommodation is another matter. A few experimental systems offer accommodation using a varifocal mirror, which actively changes its focal length (radius of curvature) in real time. This method offers a time multiplexed image set where specific HMD image locations are cycled through in the same way that frame sequential color is accomplished. Experimental work still needs to be done in determining the ideal number of focal planes and their locations in producing lifelike images. A minimal number would seem to be three located 0.3 m, 1.0 m and > 10 m from the eye.

One interesting method for accomplishing the multiple focal planes is based on the cholesteric liquid crystal (CLC) technology found in the Kaiser HMDs. Kaiser uses three wavelength specific CLCs to produce the standard color triad (red, green, blue). Because CLCs are inherently very wavelength specific, it is conceivable to use three different triads located to produce the three focal planes. Each color of each triad would use a slightly different wavelength within the red green and blue bands. The combined image would then offer three simultaneous focal planes. A z-buffer would be used to decide on which plane a given object should be located.

V. Head Motion

Head motion is dependent on application and HMD mass. Pilot HMDs require high mobility but sometimes can have a heavier display system. Pilots have custom fitting helmets that can disperse weight better than most HMDs, however, high G loads to the head need to be taken into account. Surgery requires lightness but not much motion where walk-through is just the opposite. In all cases, however, lowering the center of gravity closer to the neck will add greatly to flexibility. Figure 4 shows a poorly balanced research HMD. This is an experimental augmented reality one not meant for a consumer.

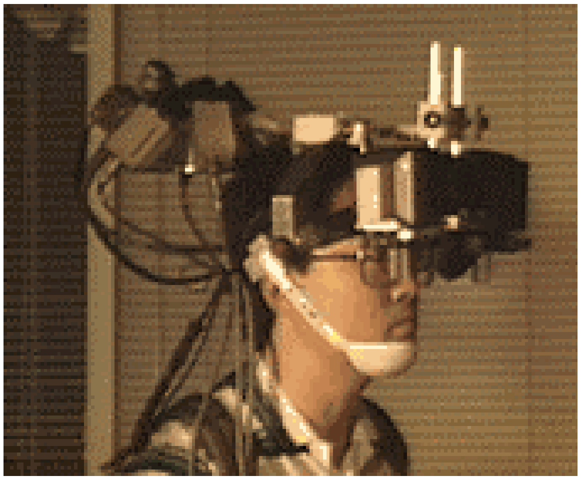

Figure 4 Poorly balanced HMD

All of the previously mentioned applications can be operated in see-through or augmented mode for which image registration and lag are the biggest problems. Total lag is the sum of the tracker lag, image generation lag and the frame buffer lag. This is normally about 50ms or longer. This causes an unwanted sensation termed “swimming” where the image is a few frames behind where it should be. This is especially aggravating in augmented systems, surgery and assembly, where registration critical.

To reduce lag, one must improve the three main sources of lag. Tracking lag can be reduced by higher sampling and update speeds – where 60 to 120 Hz is standard, UNC’s tracker system updates at 1800Hz plus, reducing lag by about 10ms with greatly increased registration. Image generation can be accelerated with faster and more efficient graphics hardware and software. Frame buffer lag can be eliminated by a technique called Frameless Rendering[3] where the order of rendering is by which pixel is needed on the video sweep and it is sent directly to the video stream. The last lag reducer is in prediction that benefits in accuracy exponentially by the reduction in lag from streamlining the standard lag areas[4].

SUMMARY

The following page is Table 1. This is a brief summary / checklist to aid in the selection of appropriate HMD technologies for various tasks.

In almost all HMDs, resolution needs improvement along with the increase of individual pixel fill factors. Many general use HMDs have acceptable optical and weight qualities to make them useful as tools. However, few designs are mature enough for convincing immersion. See-thorough designs are normally specific for an application making their costs very high and of limited general use.

HMDs have often failed to deliver the performance expected of them. This is more often than not, the result of a mismatch in form and function. While there are some limitations, careful design that considers which factors of the human visual system are necessary and to what level they are needed matched to appropriate HMD technologies will result in an acceptable HMD system.

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[3] UNC’s Frameless Rendering project

[4] Azuma

HMD Applications and Solution Forms

Application	FOV	Resolution	Color Depth	Head Mobility	Tracking	Stereo / Accommodation	Design Form
Mobil Data	30°	high	monochrome OK, color better	high	none	none	Monocle - very small / light, Flip-up, Binocular non-HMD OK
Surgery	30°	very high	very high	medium	highly registered, medium working volume, moderate lag	S: very important A: helpful	Look around, Video see-through, Flip up, Comfort for long wear times
Remote Manipulation	60°	medium	medium	low-medium	accurate, varied working volume, moderate lag	S: very important A: unimportant	Short wear times, Mechanical tracking
Pilot Optical See-Through	120°	high	high	very high	highly registered, small working volume, minimal lag	none	Integrate with helmet, Mechanical tracking, Robust
Walk Through / Immersion	≥ 120° (h) ≥ 60° (v)	medium	high	medium	medium accuracy, large working volume, moderate lag	S: important A: helpful	Very light, Untethered, Large vertical FOV
Entertainment	60°	medium	medium	high	low accuracy, varied working volume, moderate lag	S: useful A: unimportant	robust

Table 1. This table summarizes the minimum acceptable performance criteria for various HMD applications.

ACKNOWLEDGEMENTS

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