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February 1993

Paul J. Hezel
Harry Veron

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MITRE
Bedford, Massachusetts

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SECTION 1

INTRODUCTION

One of the goals in the development of Virtual Reality (VR) is to achieve "total immersion" where one sees and interacts with objects in a virtual world in the same way that one sees and interacts with the objects of the real world. One becomes immersed in another world through the sense of sight. Thus the technique of displaying a virtual environment determines, in part, the degree to which one can become transported out of the real world and into the virtual world.

The developers of VR have utilized the head mounted display (HMD) as a means of displaying the virtual environment to the user. The HMD is not new but has seen widespread use as an information display in military aircraft. In an HMD, displays and imaging optics mounted on a headset provide a virtual image in front of the eyes. In the VR domain, this design provides the user with a view of the virtual environment while blocking out the user's real environment. A tracking device allows the computer to present a viewpoint corresponding to the user's head position and orientation, thus enabling freedom of movement for the user within the virtual environment. These and other characteristics enhance the total immersion capabilities of the HMD.

Several HMDs are commercially available for VR applications, including the Eyephone made by VPL Research Inc. of Foster City, CA, the Cyberface made by LEEP Systems in Waltham, MA, the Flight Helmet made by Virtual Research in Sunnyvale, CA, and the Virtual Reality Group HMD, made in Vienna, VA. Other prototypes have been developed at research centers, such as University of North Carolina, the Air Force Institute of Technology in Ohio, the NASA/Ames Research Center in Moffett Field, CA, and the Naval Ocean Systems Center in San Diego, CA. Factors that limit the ability of these devices to achieve total immersion include the lack of a high resolution image, variable focus optics, and a wide field of view (FOV).

This report is an assessment of the present state-of-the-art in HMD technology applied to VR. It describes the technical capabilities of existing HMD configurations and evaluates these characteristics with respect to immersive VR. We conclude that major advances are required in HMD technology to achieve an adequate immersive VR environment and user acceptance.

1.1 SCOPE

Closed system HMDs are evaluated in this report on the basis of quantifiable factors relating to their physical performance, such as FOV and visual resolution. Closed system HMDs allow only the viewing of a single virtual image, as opposed to open system HMDs, which overlay a virtual image on a real world image. Possible enhancement of immersive VR due to the use of various other input/output devices in conjunction with the HMD, such as the DataGlove and tracking devices, is beyond the scope of this paper. Perceptual biases among individual users affect the degree of immersion experienced through VR [Ellis]. Evaluation of these are also beyond the scope of this paper for obvious reasons.

1.2 DOCUMENT ORGANIZATION

The report is structured as follows: section 2 of this report gives an overview of HMD design and delineates the goals for this form of display of Virtual Reality. Section 3 gives a technical assessment of current HMD technology mirroring the criteria described in section 2. Section 4 contains conclusions and recommendations about HMD technology.

SECTION 2

OVERVIEW OF HMD DESIGN

2.1 BASIC STRUCTURE

Current VR HMDs consist of four basic parts: 1) a display or image source, usually a cathode ray tube (CRT) or a liquid crystal display (LCD), which presents an image to the viewer. For binocular viewing, two displays are required, one for each eye; 2) an optical system that allows the screen to be placed very close to the eyes and head for compactness, magnifies the image so it appears "life size," and ideally provides a wide FOV; 3) a head mount, which provides a base for mounting these components; and, 4) a position tracker, which monitors the head position of the user. The computer uses this information to generate an image corresponding to the user's head position and orientation (figure 1).

2.2 VIRTUAL REALITY GOALS

People are accustomed to the way they already see the real world. A virtual environment, which parallels the conditions of sight in the real world, will be both useful and widely accepted. Therefore, we establish goals for the display quality of the HMD with regard to the characteristics of normal visual sight. These are:

1. Three dimensional (3D)/binocular viewing
2. FOV
3. Resolution
4. Color
5. Freedom from distortion and aberrations
6. Accommodation (focus) over a range of viewing distances

In addition, the HMD must be constructed in such a manner that it is easy and comfortable to use:

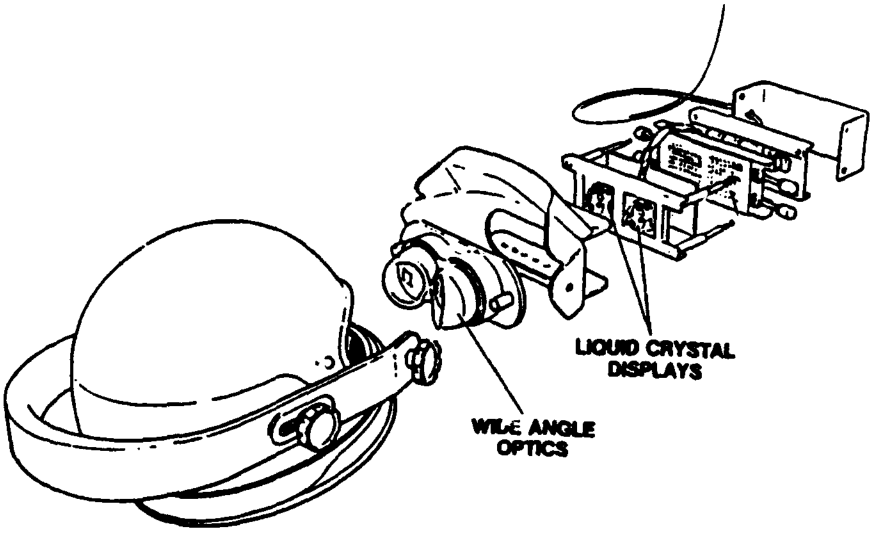

Figure 1. A Head Mounted Display for Use in Virtual Reality

1. It should be adjustable for physical variations between users - head size, and interpupillary distance (IPD).

2. There should be minimal physical restrictions relating to weight and tethers.

All of these characteristics are both necessary and desirable for the HMD to provide an effect of total immersion that matches the viewer's natural experience. Realizing, however, that the reproduction of normal vision in an HMD or with any other current display device might be beyond the ability of current display technology, we set realistic goals for the visual quality of HMDs. These suggested goals are a compromise between those characteristics, which reasonable advances in current technology should be able to provide and those that humans will find usable. Table 1 compares the natural human visual characteristics to the suggested goals for HMD visual characteristics.

Table 1. Suggested VR HMD Goals versus Human Visual Performance

	Binocular Overlap	Total FOV	Resolution	Color	Weight	Tethers
Human Vision	120 deg	180 deg H 135 deg V	1 arc-min/ element	greater than 1,000,000	N/A	N/A
Realistic HMD Goals	70 deg	140 deg H 100 deg V	2 arc-min/ element	32,768 distinguishable	12 ounces	none

2.2.1 3D/Binocular Vision

Binocular vision is an important depth cue. A slightly different perspective of an object presented to the right and left eyes is fused by the brain, which enables us to perceive an object in three dimensions. Depth perception provided by binocular vision must be carried over into the virtual environment in order for the user to function naturally in VR. It allows the user to make correct judgments about the relative positions of objects.

2.2.2 Field of View

The monocular FOV of the human eye is 150 degrees in the horizontal and 135 degrees in the vertical [Clapp]. The total horizontal FOV is 180 degrees (without head motion). Thus there is a natural binocular overlap of about 120 degrees. The FOV of the HMD must approximate this as much as possible for the use of the peripheral field and the illusion of total immersion.

2.2.3 Resolution

The human eye is capable of discerning an element size corresponding to about 1 minute of arc at the very center of the person's gaze. The resolution capability of the eye falls off rapidly with the angle from the center of this area of high resolution capability. Assuming that the HMD technology allows eye motion and thus any point in a given FOV could be the focus of a person's gaze, a 50 degree monocular FOV would have to contain at least 3000 white pixel elements to render this resolution. Although this resolution would be desirable, current display technology cannot provide this resolution in a 4-inch diagonal or smaller display, the size of the displays typically used in the HMD. A more reasonable goal for HMD resolution might be 2048 x 2048, which is currently achieved with large surface CRT technology. On the other hand, a 1280 x 1024 white pixel matrix in a small display is the minimum acceptable resolution needed to take advantage of present commercial workstation image generating capabilities.

2.2.4 Color

Since people are used to viewing the world in color, a full-color display would add to the realism of the system. Color can also be used for coding in various applications. From current experience, graphics workstations require a frame buffer at least 24 bits deep for suitable high quality color applications. This represents over 16 million colors. However, the display may not be able to reproduce all of the distinct colors. As a minimum, 15 bits should be required. Therefore, a color palette with 32,768 colors is anticipated from the display.

2.2.5 Freedom from Distortion and Aberrations

The environment is perceived by the eyes in an orthoscopically correct manner. The proportions of viewed objects are realistic and not compressed, elongated, bent, or distorted in some other way. A straight line is a straight line and does not appear to be anything else. Colors are usually continuous over the object from which they are reflected. A virtual environment image must reflect these qualities of the real world, free from geometric distortion and chromatic aberrations, which would affect the user's perception of an image. Misjudgments that are possible in a distorted environment might also affect the user's performance in that environment.

2.2.6 Accommodation/Convergence

The human eyes accommodate, or focus, and converge to the same point in space when viewing an object in the three dimensions of our natural surroundings. The simultaneous accommodation and convergence of the eyes allows one to comfortably view objects that range in distance from infinity to the individual's near point of accommodation, a distance of about 0.25 meters. Ideally, we would like to have the same viewing range with an image provided by the HMD.

2.2.7 Adjustable Elements for User Variation

The physiological makeup of each person is not the same. Therefore, adjustable elements must be incorporated in the design of the HMD to account for differences in head size, IPD to accommodate binocular viewing, and the wearing of eyeglasses.

2.2.8 Physical Limitations

An ideal HMD for use in VR should weigh no more than an average pair of eyeglasses and be as easy to place on and off. This is not within the realm of current technology. The weight of the HMD must be minimized to avoid neck strain, user fatigue, and gain user acceptance. An acceptable maximum weight for the HMD is about 12 ounces.

Free range of movement is desired when working in the virtual environment. An HMD should be constructed without counterweights and tethers that seriously impede the user's free range of movement.

2.3 HMD OPTIC DESIGN FEATURES

The significant differentiating factor in HMDs used for VR is the type of optical system used. The type of optics determine the other parameters of the system, such as FOV and accommodation/convergence range.

2.3.1 Infinity Optics

The use of infinity optics in the HMD is derived from the heads up display (HUD) used in military aircraft. In the HUD, the so called set of infinity optics collimate the rays from the image source to produce an image that appears at infinity (figure 2). This virtual image is then overlaid on the real scene in front of the pilot. The advantage of this approach is that it eliminates the need for the pilot to look down at the flight instruments.

The application of infinity optics in HMDs is the same as in the HUD. Rays from the display are collimated to appear as though they are projected from infinity. The infinite virtual image allows the eyes to remain focused and converged at infinity.

Designs employing infinity optics in conjunction with CRTs have been used in prototypes built at Air Force Institute of Technology, Naval Ocean Systems Center (NOSC), and in the commercially available VR Group HMD. The CRTs are mounted either on the front of the head directly facing the eyes as in the NOSC HMD (figure 3), or on the side of the head, using relay optics to project the image to the eye, as in the VR Group HMD (figure 4).

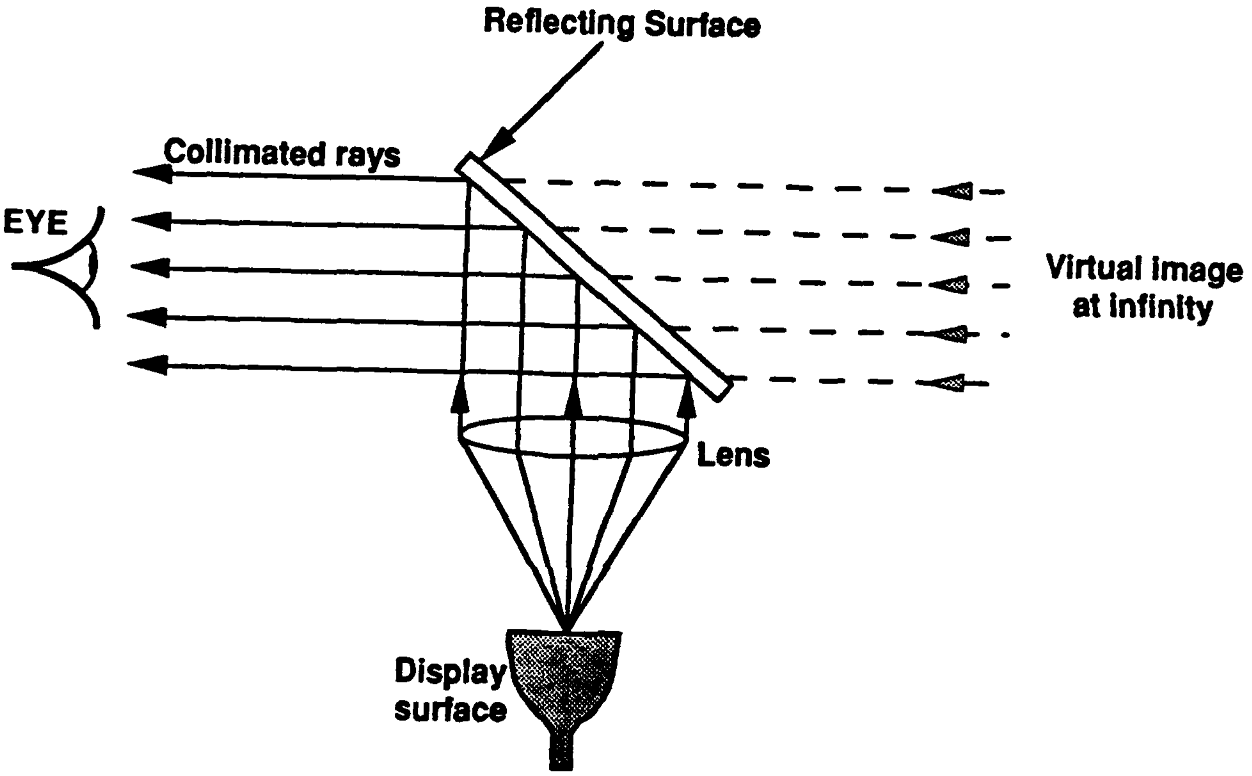

Figure 2. Rays from the CRT Are Collimated by the Lens to Produce an Image of Infinity

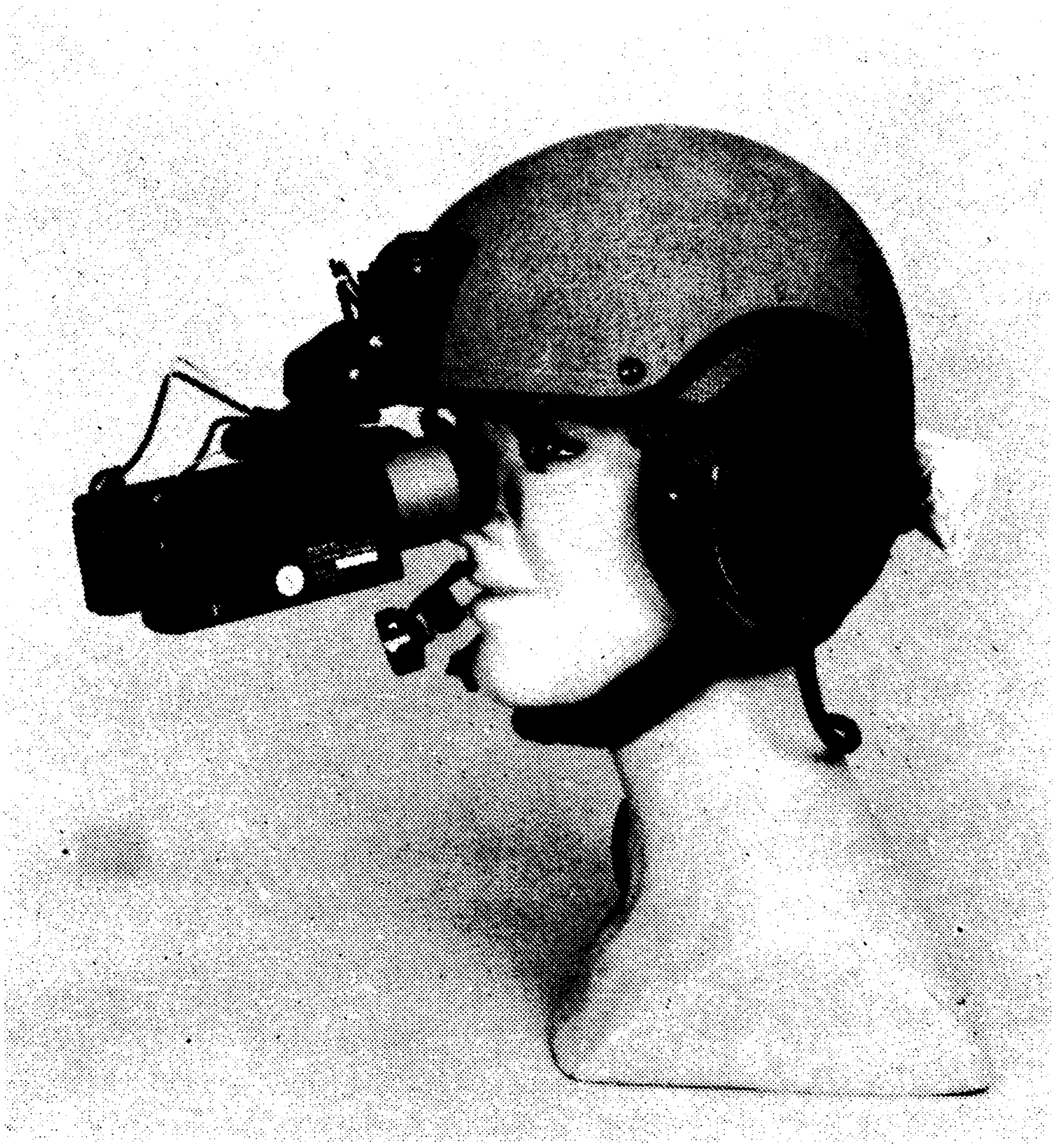

Figure 3. The Naval Ocean Systems Center HMD with Front-Mounted CRTs

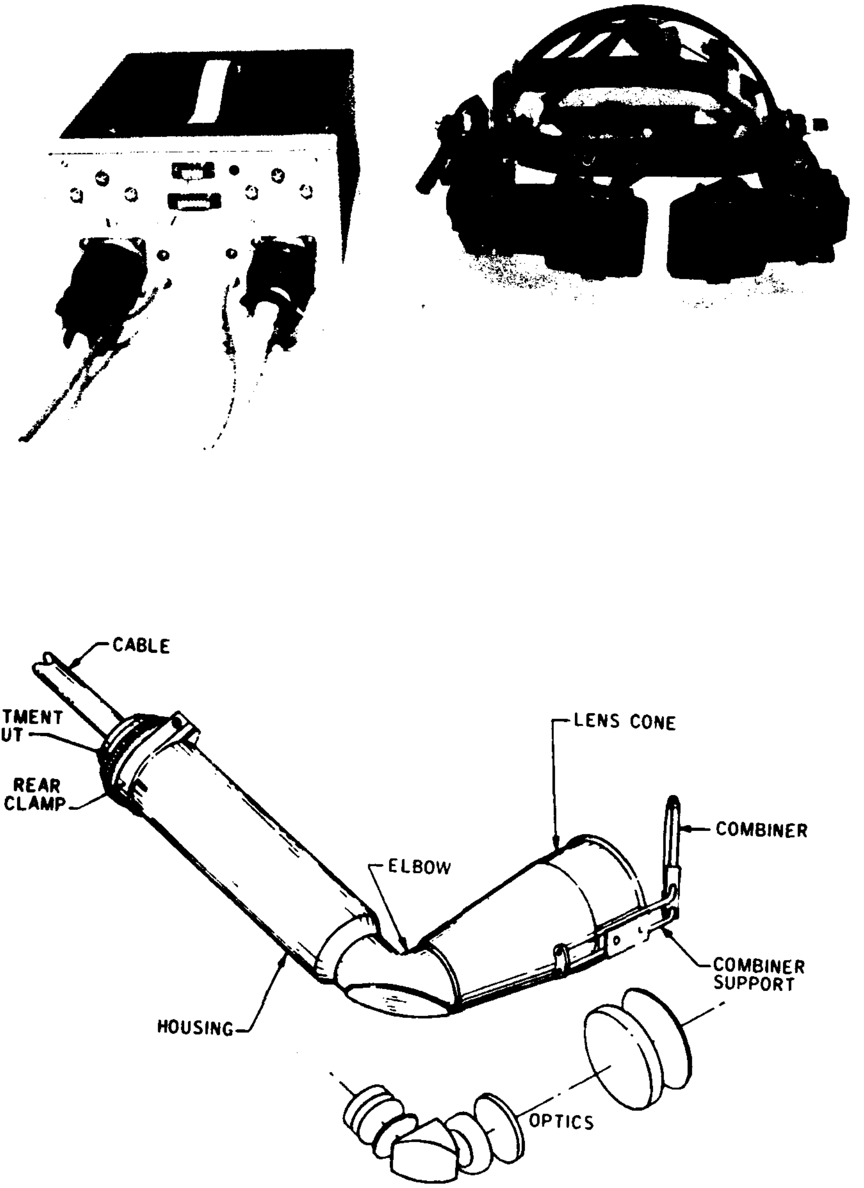

Figure 4. The VR Group HMD with Side-Mounted CRTs. The Image is Projected in Front of the Eyes by Means of Relay Optics and Mirrors

2.3.2 Magnifier Optics

The other type of optical system is a magnifying system. It produces a virtual image plane somewhere within the range of 0.4 m to infinity, depending on the focal lengths of the lenses and the relative placement of the displays and lenses (figure 5).

Eric Howlett of LEEP Systems in Waltham, MA, designed a wide angle set of optics for viewing stereoscopic photographs taken with a stereoscopic camera. Essentially a wide angle magnifier, the LEEP optics compress most of the information into the central portion of the FOV. The LEEP optics have been applied to HMDs for use in conjunction with LCDs. They provide a horizontal FOV of up to 140 degrees. Virtual Research, AFIT, and NASA use LEEP optics in their HMDs. They are also used in LEEP Systems' commercial product called the Cyberface. Figure 6 shows a picture of Virtual Research's Flight Helmet.

VPL has also developed a set of magnifying lenses for their Eyephone HRX after using LEEP optics in an earlier model. They now use a set of Fresnel lenses, which are lighter and produce less geometrical distortion than the LEEP optics.

Also of interest is Fake Space Lab's Binocular Omni-Orientation Monitor (BOOM). It incorporates LEEP magnifier optics with CRTs in a device that does not sit on the head but is mounted to a moveable arm (figure 7).

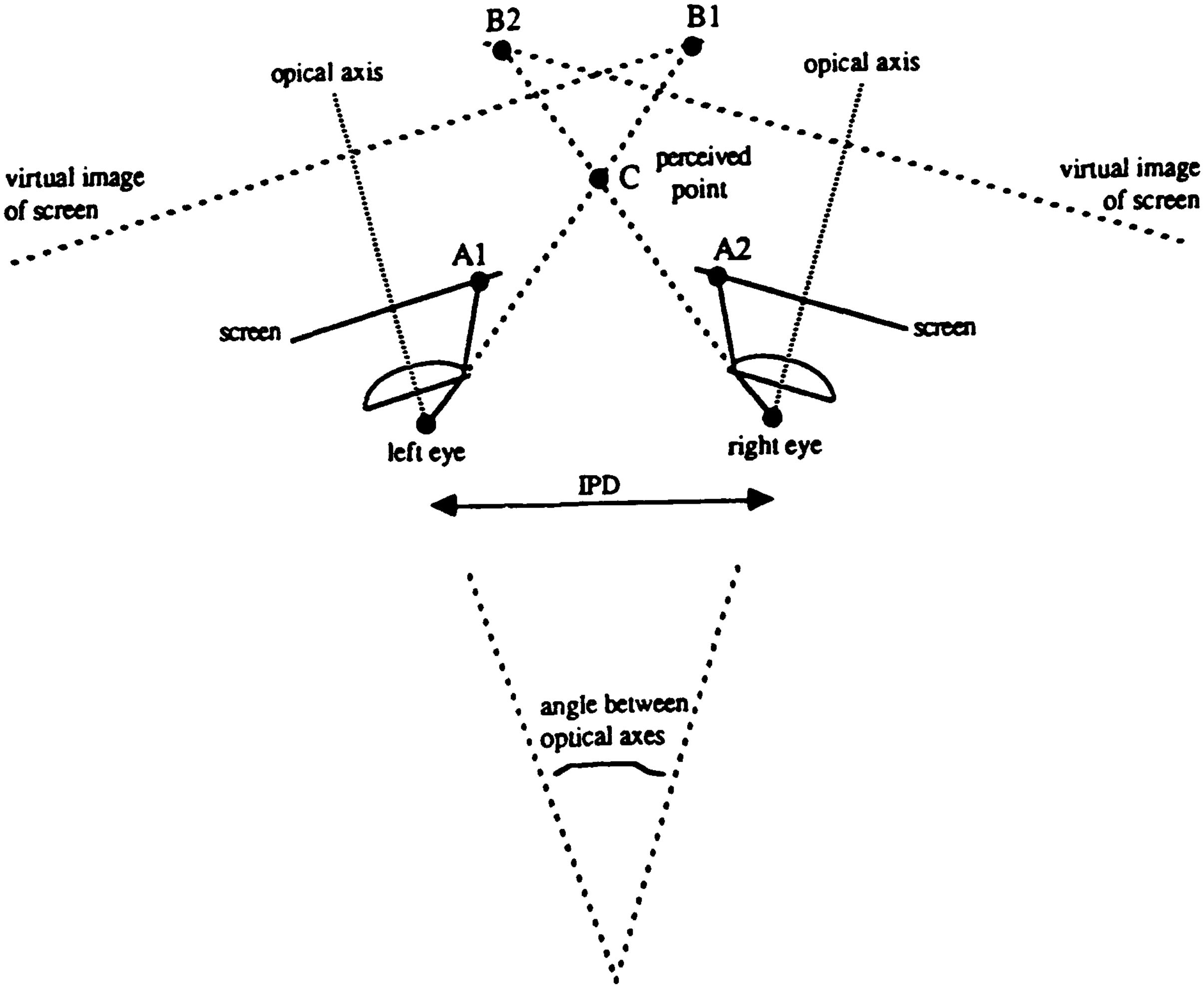

Figure 5. Magnifier Optics Produce Virtual Images of the Display Screens

Figure 6. The Virtual Research Flight Helmet

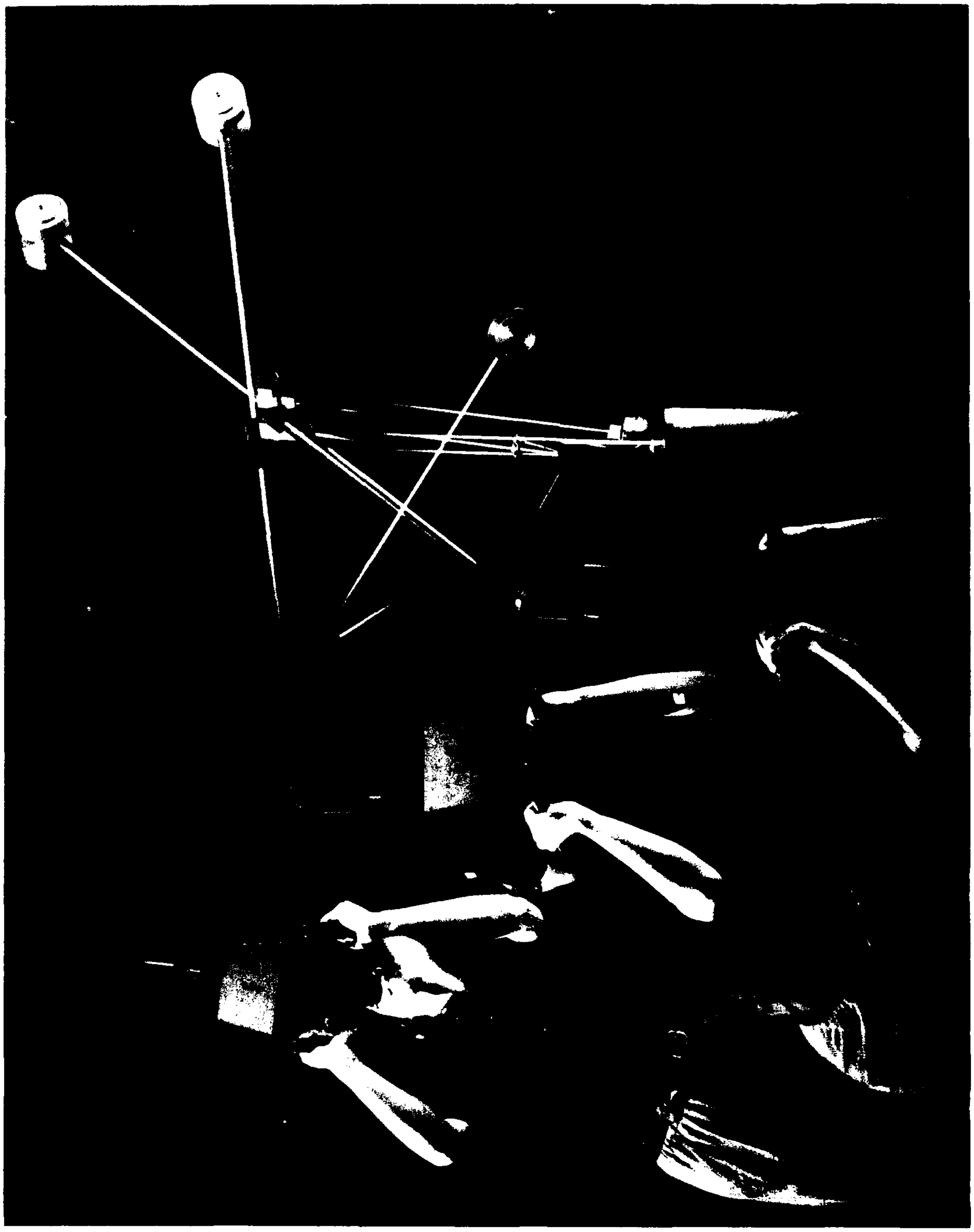

Figure 7. Fake Space Lab's Boom

SECTION 3

TECHNICAL ASSESSMENT

3.1 UNDERLYING TECHNOLOGY

There are certain factors that impose limits on the visual quality and size of HMDs that can be engineered for VR use.

3.1.1 Resolution

Achieving adequate resolution is an important challenge facing current HMD designs. The CRT is useful because it currently provides the highest resolution available, a 1280 x 1024 matrix in a *monochrome* 1-inch display. The physical makeup of the CRT, however, will not allow further reduction in size and weight to make it applicable for use in VR HMDs. A display slightly less than 1 inch in diameter weighs between 3.5 and 6 ounces and is at least 4 inches in length [Hughes]. The LCD, on the other hand, has a relatively small weight (2.8 to 6.3 ounces) for the larger 3-inch to 4-inch screen and is less than 1 inch thick [SHARP bulletin]. The resolution, however, is no better than one-third of the resolution of the CRT. Unfortunately, there is not a large enough demand for higher resolution LCDs to warrant their further development for this particular application.

A possible solution to the resolution problem is the development of area of interest (AOI) displays. These involve the use of a high resolution insert in a low resolution peripheral view. LEEP Systems is currently developing such a dual resolution system, incorporating LEEP Optics with two different LCD screens for each eye.

Another possibility is the incorporation of Tektronix Liquid Crystal Shutters. The system preserves the monochrome CRT resolution in a color image by using a field-sequential color display. The absence of the three-color phosphor triad in this system may be a solution to some of the current problems with resolution under magnified conditions. However, this approach would add more weight and tethers to the existing HMD configuration.

3.1.2 Accommodation/Convergence Conflict

Associated with the binocular viewing of stereoscopic images is the accommodation/ convergence conflict. In the real world, the eyes accommodate and converge to the same point. The lack of conflict in natural viewing allows us to view images clearly over a large range of distances. In stereoscopic viewing, on the other hand, the eyes no longer accommodate and converge to the same point. This is caused by the fact that a pair of two dimensional images is perceived as an image in three dimensions. The eyes can comfortably tolerate only a certain amount of discrepancy between accommodation and convergence angles [Lipton]. This effectively sets limits on the viewing range of the display unit, which depends on the placement of the virtual image plane. The HMD must be designed with these constraints in mind.

The 3D effect is achieved by presenting a slightly different view of an object to each eye. The two images are horizontally offset by a distance that is referred to as the parallax (figure 8). The amount of parallax determines the apparent position of the object in relation to the screen. Negative parallax places the image in front of the screen. In this case, the right and left images are interposed. Zero parallax places the image on the plane of the screen. Positive parallax places the images behind the screen (figure 9). If the parallax is greater than the interocular distance of the eyes, the eyes would have to diverge to fuse the images. Divergence must be avoided because it is unnatural and puts strain on the eyes.

A guideline for comfortable viewing of a stereoscopic image is a 1.6 degrees maximum change in convergence angle [Lipton]. In figure 8, this change in convergence angle is (Beta) - (Alpha). The maximum screen parallax that gives rise to the 1.6 degree change in convergence angle can be expressed as $P_{max} = 0.03 \times D_{screen}$. P_{max} is the maximum screen parallax and D_{screen} is the distance between the eyes and the viewing plane [Veron et al, 1989]. For viewing objects at infinity, the viewing plane must be set at least 2.3 m from the eyes [Veron et al, 1989]. To view objects that would be within working distance, about 0.5 to 1 m, the image plane would have to be at about 0.6 m from the eyes.

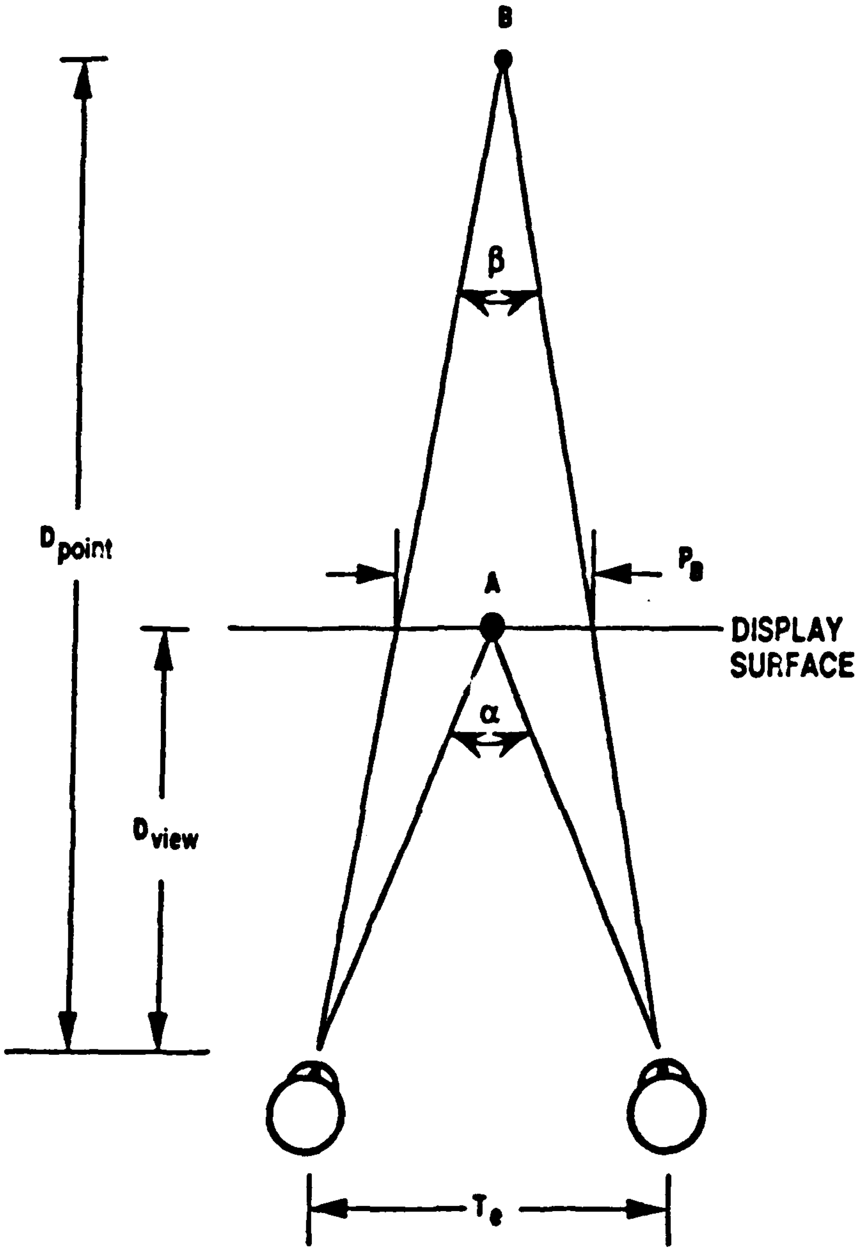

Figure 8. The Distance between Corresponding Points of the Right and Left Eye Images on the Screen Is the Parallax, P_B. It Determines the Distance in Front or Behind the Screen at which the Image Appears

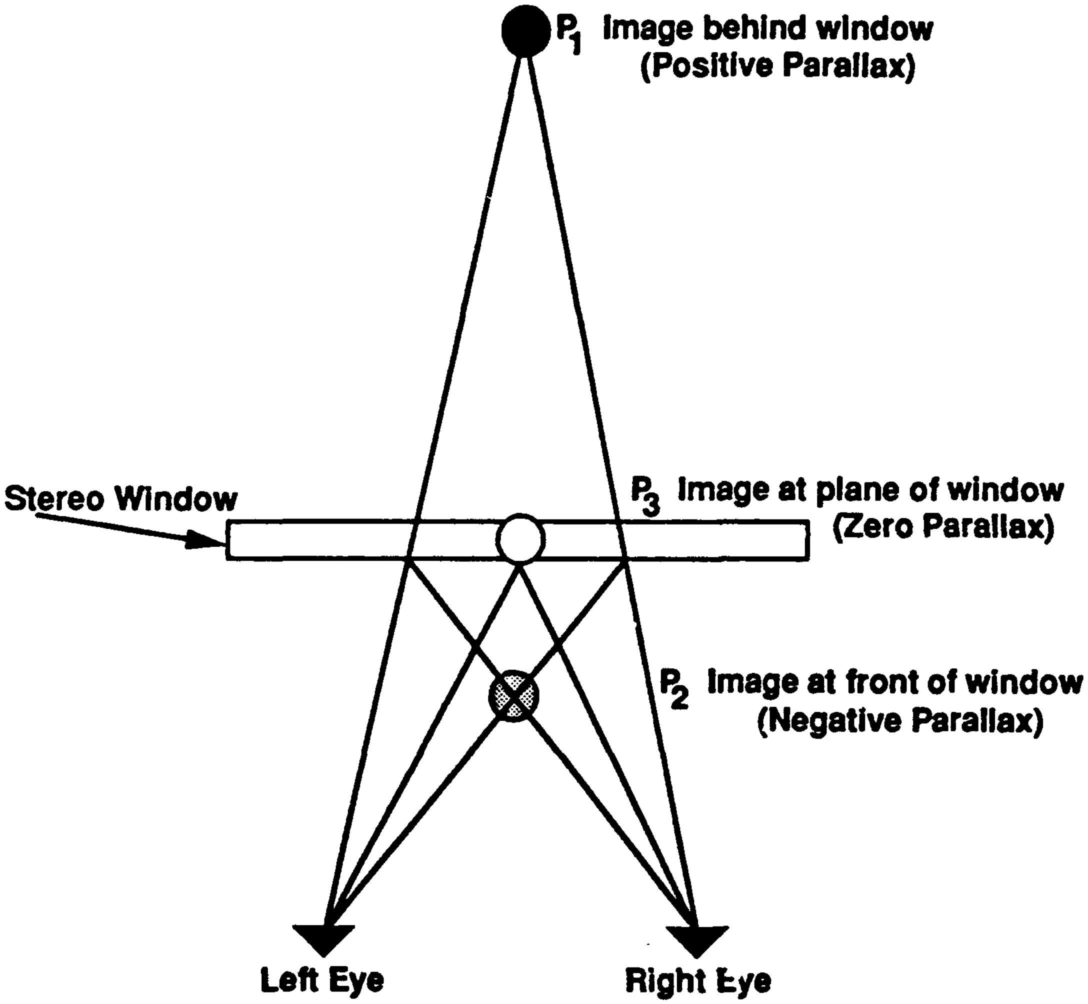

Figure 9. Examples of Positive, Zero, and Negative Parallax, and the Corresponding Positions of the Perceived Image

Physically, it is impossible to overcome the accommodation/convergence conflict in a binocular optical system where the virtual image plane is at a fixed distance from the user. It remains a possibility to develop a bimodal system where the image plane can be adjusted between one of two choices, thus allowing accommodation over the whole range of distances [Veron, personal communication, 1992]. The closer image plane would allow the user to work with objects up close in three dimensions. Binocular vision would provide the strongest depth cue in this mode. A more distant image plane would allow visualization of distant objects. If the distance to the objects in this plane is sufficiently large, a single image can be presented to both eyes, since the binocular depth cues are not effective at such distances. This would increase graphics rendering speeds because only one image instead of two images has to be calculated. Depth perception in this case is reliant on other cues, such as interposition and relative size.

Only through a variable virtual image plane system will the conflict of accommodation and convergence be resolved so that viewing can take place over a normal range of distances. A method of making the transition from one viewing plane to the other would have to be worked out.

3.1.3 Misaccommodation

Some problems of misaccommodation and spatial disorientation with military HUDs and HMDs have been documented [Biberman, Hale, Roscoe]. It has been found that the eye does not have a resting point of accommodation at infinity, but instead at a distance of about 1 m from the eyes, varying among individuals. This is believed to have caused problems with orientation and spatial judgments in aircraft. The effects of misaccommodation in relation to closed system HMDs like those in VR have not been studied in detail.

If there is a misaccommodation/spatial misjudgment problem, it must be determined whether the source of the problem is due to the physiological makeup of the user's eyes, or whether it is a problem inherent to the use of an artificially created 3D image. In either case, it also must be determined whether the HMD system design can correct these problems, especially if the problem is user specific.

This leads to another problem: can VR images be created to match the spatial relationships of the real world? In an open system, the overlay of the virtual image on the real world absolutely requires that the perceived spatial relationships be matched. In a closed HMD, it would be desirable to match the spatial relationships of the virtual world to those of the real world, since the user is already used to his perception of the surroundings. In a training simulation, correct spatial simulation may be required if what is learned is to be carried into the real world environment. However, it is possible that spatial relationships could be relearned in the virtual environment. The problems and solutions related to misaccommodation and spatial misjudgment require further investigation [Hale].

3.1.4 HMD Physical Configuration

The components of the HMD--the display screens and the optics--have intrinsic size and weight. The incorporation of these components into an HMD limits the extent to which the size and weight can be reduced. Thus the reduction to an acceptable level of size and weight will have to be achieved through reduction in size and weight of the components.

3.2 PRODUCT ASSESSMENT

The characteristics of existing HMDs, which are discussed below, are summarized in table 2 for comparison.

3.2.1 3D/Binocular Vision

Most of the HMDs intended for VR use incorporate binocular vision for depth perception. However, binocular convergence is virtually the same from 20 feet on out to 2000 feet [Merritt]. Therefore, when the images to be viewed are beyond 20 feet, binocular vision can be replaced with vision of a single image, where the same image is presented to each eye.

Table 2. Comparison of Specification of Existing HMDs

Company	HMD Name	Optical System	Display	Total FOV (Degrees)	Addressable Resolution*	Resolution** (arc-minute)	Color	Weight	Cost
VR Group	HMD	Infinity	CRT	66 H/50 V	1280 x 1024	2.3 H x 2.9 V	Mono	3.0 lbs.	$60K
LEEP	Cyberface 2	LEEP	LCD	140 H/95 V	479 x 234	21 H x 44 V	Color	2.5 lbs.†	$8.1K
Virtual Research	Flight Helmet	LEEP	LCD	100 H	360 x 240	19 H x 28 V***	Color	3.7 lbs.	$6K
Fake Space Labs	BOOM 2C	LEEP	CRT	110 H/90 V	1280 x 1024	4.2 H x 5.3 V	2 Color	N/A	$74K
VPL	Eyephone HRX	FMT (fresnel)	LCD	106 H/75 V	720 x 480	12 H x 15 V	Color	2.5 lbs.	$49K
AFIT 1989		LEEP	LCD	55 H	360 x 240		Color		N/A
NASA/ Ames		LEEP	LCD	120 H/120 V			Mono		N/A
UNC see-through		Mirrors/ magnifiers	LCD	25 H	320 x 220		Color		N/A
NOSC HMD I		Infinity	CRT	40 H	700 TVL/PH		Mono	6.2 lbs.	$27K
NOSC HMD II		Infinity	CRT	55 H	250 TVL/PH		Mono	5.8 lbs.	$3K

* Reported addressable resolution.

** The resolution follows Dunn-Roberts' calculations (appendix A). This refers to the white picture element of the LCDs.

*** Based on the assumptions that the monocular FOV is 66 degrees as given in the LEEP standard product guide.

† The Cyberface 2 weights 4.25 pounds with the Counterpoise.

The image presented should also have appropriate depth cues of perspective, size, and interposition. The benefits of providing stereoscopic vision beyond 20 feet could be minimal [Veron, personal communication, 1992].

At close range, binocular vision is essential for good 3D perception. The region of binocular overlap, where the two monocular fields of view overlap, determines the percentage of the total FOV, which can be viewed stereoscopically. This consideration is important in the design of the optical configuration of the HMD and the design of graphics presented to each eye. There are three options for the alignment of the optical axes of the HMD that affect the binocular overlap: parallel, divergent, and convergent (figure 10). Infinity optics use parallel optical axes. This minimizes the FOV, but the overlap is very large, allowing a large field for stereoscopic perception. The VR Group HMD with its parallel axes claims to have a variable amount of overlap with settings at 35, 67.5, and 100 percent. Diverging axes extend the binocular field, but decrease the binocular overlap. The LEEP Systems' Cyberface has diverging optical axes of 25 degrees. The result is that the binocular overlap area is much smaller.

3.2.2 Field of View

Infinity optics have achieved a maximum monocular FOV of 50 degrees diagonal in the VR Group HMD. This results in a maximum total FOV of about 82.5 degrees for a 35 percent overlap setting. For VR use, the FOV of the infinity optics is further limited by two main factors: size of the display and small exit pupil.

Because of its size, usually on the order of 0.5 to 1 inch diagonal, the CRT display is not conducive to a wide FOV. A larger CRT, which could provide a significantly larger FOV, is not feasible because of the weight added to the HMD. The size of the exit pupil of the optics, about 12 mm, combined with an eye relief of about 30 mm needed to accommodate eyeglasses, further decreases the FOV. The effect caused by the exit pupil is the same as that achieved when peering through a knothole. When right up next to it, the FOV is large, but looking

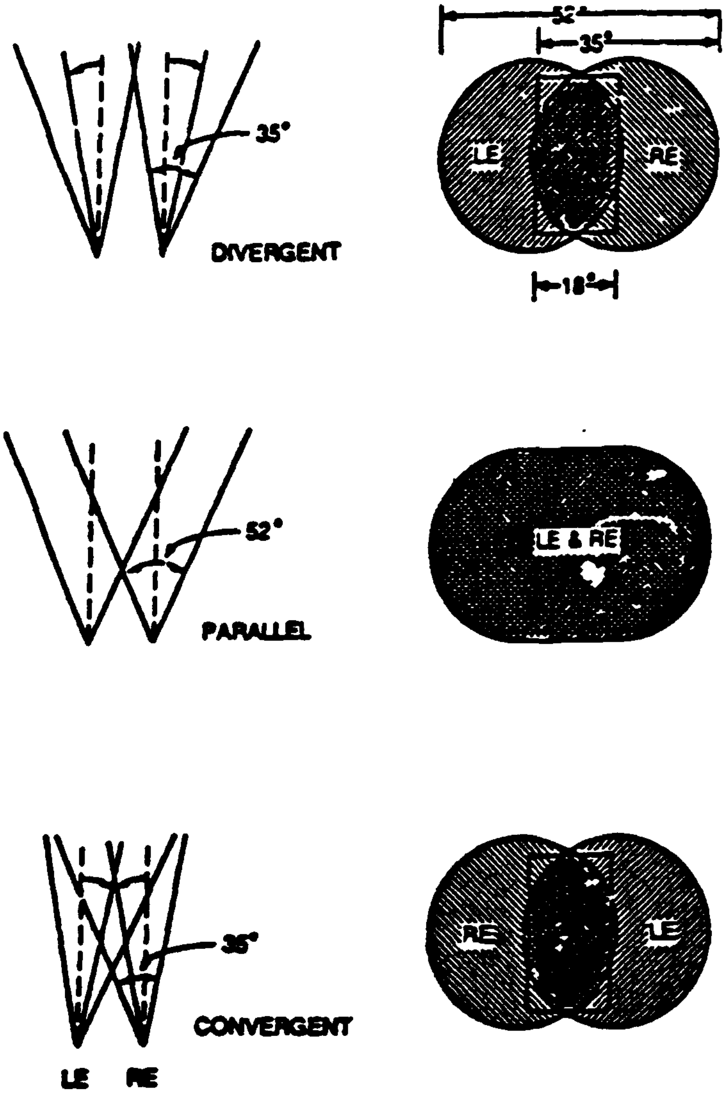

Figure 10. Binocular Overlap of Divergent, Parallel, and Convergent Optical Axes

through it from a distance of a foot, the FOV decreases dramatically (figure 11). Because of the relatively small FOV, infinity optics produce a tunnel vision effect. This is felt to be undesirable for most VR applications.

Magnifier optics can be constructed to easily produce a wide FOV, as in the case of LEEP optics. The FOV is enhanced by the 69 mm diameter of the optics. The LEEP Systems Cyberface uses a 4-inch LCD to make full use of the visual field of the optics. The Cyberface obtains a 140 degree total field in the horizontal direction. Other applications of the LEEP optics use a 3-inch LCD. This does not fill out the potential FOV of the optics [LEEP Systems, Standard Product Guide]. Setting the optical axes parallel to each other reduces the FOV but increases the binocular overlap. The Virtual Research Flight Helmet with its parallel axes achieves a total FOV of 100 degrees, which is about 40 degrees less than the Cyberface 2.

LEEP optics are used with CRT displays in Fake Space Labs' BOOM counter-balanced arm device. This allows the wide FOV to be used in conjunction with the high resolution image. The use of LEEP wide angle optics with CRT displays in an actual HMD is contraindicated by the fact that a small 1-inch display would not fill up the visual field of the optics.

An incorrect FOV can also be presented to the user if the eyes are not in the expected position with respect to the optics which corresponds to the calculated point from which the scene should be viewed. Because the eyes will not always be in this expected position, the sight lines to the image will not be correct, thus the scene will not be perceived correctly [Robinett].

3.2.3 Resolution

Current CRTs used in infinity optics provide 1280 x 1024 addressable elements in a 1-inch diagonal monochrome display. The CRT display used in the VR Group HMD yields an addressable resolution of 2.3 arc-minutes horizontally by 2.9 arc-minutes vertically per pixel. The pixel size is 18 microns, which yields an apparent size of only 0.09 mm per pixel under

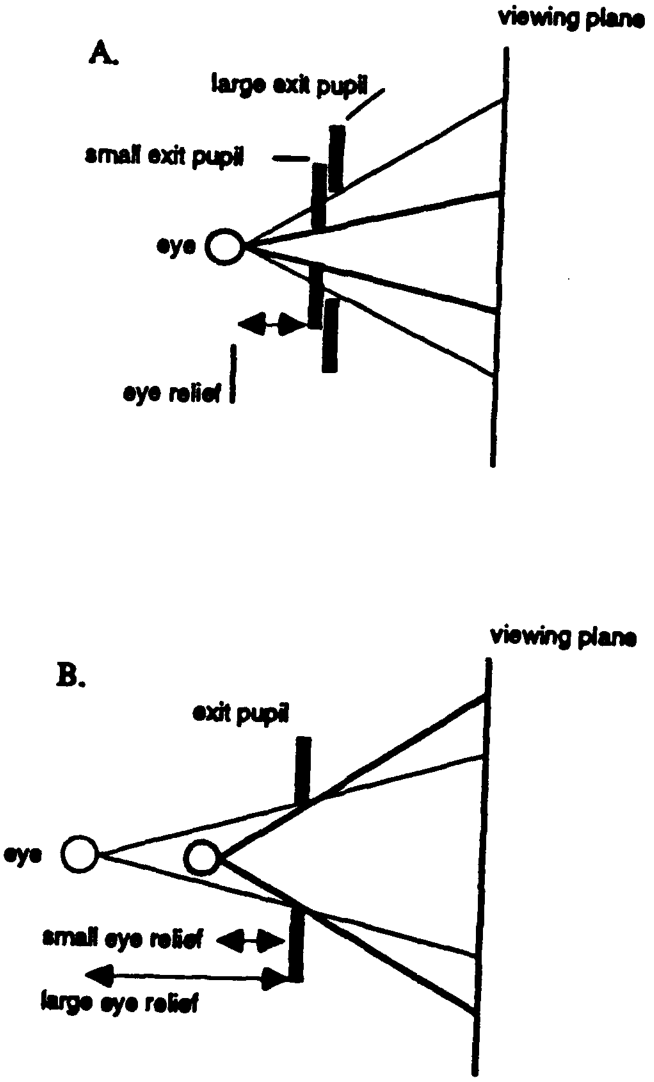

Figure 11. Effects of Small or Large Exit Pupils on FOV

the 5x magnification of the optics. The figures for resolution given in this section are calculated based on the method given by Dunn-Roberts in the appendix of his report. A reproduction of this appendix is given in appendix A.

A LCD display, as used in LEEP Systems Cyberface 2, is a 4-inch diagonal full-color LCD that renders a white pixel matrix of only 319 x 117. The white pixel size is 0.26 mm x 0.53 mm. The resolution given by LEEP Systems at the center of the screen in radians was obtained by dividing the white pixel size in mm by the axial focal length of the optics (given as 42 mm for the LEEP lenses). The pixel pitch, given as pixel size in mm divided by the focal length, converted to arc minutes yields a resolution of 21 arc minutes horizontally by 44 arc minutes vertically per white pixel. These are exceptionally large. The pixels at the edges of the screen are even larger due to the nature of the distortion of the optics.

The VPL Eyephone HRX boasts an individual color element matrix of 720 x 480, or approximately 416 x 277 white pixel elements. In a calculation by Dunn-Roberts, this yields a resolution of about 12 arc minutes horizontally by 16 arc minutes vertically per white pixel element (see appendix A). The resolution of LCDs, when compared to the high resolution capability of the eye, represents the greatest problem with LCD-based HMDs. With a CRT, the resolution is enhanced by a factor of at least five.

The magnification provided by two separate systems illustrate some of the problems involved with the resolution of the displays. The Cyberface magnification power is 6.5x. This yields a virtual pixel size of 1.7 mm x 3.5 mm at the center of the screen. Toward the edges of the FOV, the pixels are much larger because of the nonuniform compression of the LEEP optics. With 3-inch LCDs, as in the case of the Virtual Research Flight Helmet, the magnification is about 9.6x, yielding magnified virtual pixel sizes of 2.4 mm x 5 mm. The individual color pixels are discernible. The image becomes a collection of colored blocks rather than a smooth, continuous picture. The images overall are unacceptable due to the low resolution of the LCDs and the small FOV of the CRT systems.

Another problem with the LEEP Systems' Cyberface and other LCD HMDs is that the image is defocused as a means of decreasing the granularity (low pass spatial frequency filtering). The problem is that the eyes are no longer able to accommodate, thus there is no longer accurate depth perception. Furthermore, it is impossible to distinguish detail in an unfocused image.

3.2.4 Color

The LCDs currently being used are capable of marginally generating adequate color combinations for VR use. Problems arise because the RGB color elements, grouped to form a white pixel, become visible under magnification. The pixels are no longer fused to create the impression of different colors.

The same problem can occur when a color CRT image is magnified. The use of a monochrome display eliminates this problem, but a monochromatic image is not desirable for immersive VR displays.

3.2.5 Distortion and Aberrations

Wide angle magnifier optics introduce geometric distortion and chromatic aberrations to the image when used with both CRTs and LCDs. The LEEP optics induce severe pincushion distortion (figure 12). This can be corrected for in the generated graphics, but is costly in terms of the required processing. If the distortion is ignored, the user may be able to adapt to it, but the correct visual spatial relationships may no longer be preserved, thus inhibiting performance in the virtual environment.

3.2.6 Accommodation/Convergence Conflict

The infinity optics produce an apparent screen distance of about 7 m. Using the geometry of Southard's stereoscopic vision system [Veron, et al], a minimum image convergence distance of about 1.8 m is calculated. This is too great a distance for a person to

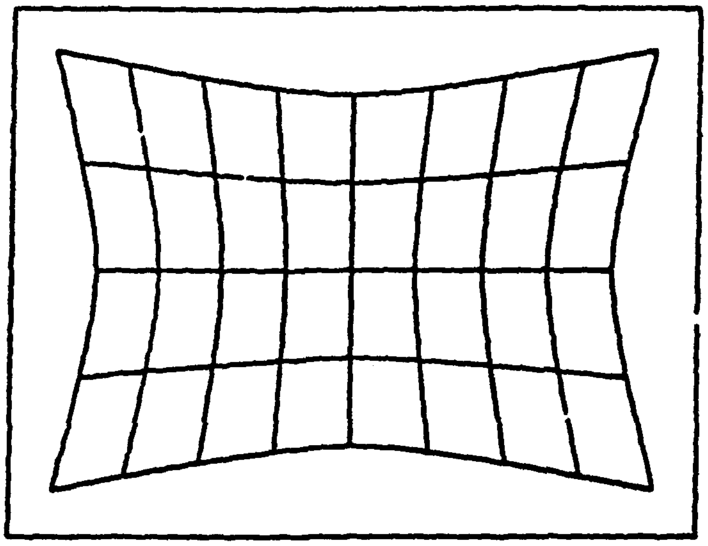

Figure 12. LEEP Pincushion Distortion of a Rectangular Grid

physically interact with one's hand in real space. The infinity optics are useful in cases where it is only necessary to view distant objects. This defeats the interactive application of VR, unless it is done under conditions of different spatial relationships.

The magnifier optics create variable image plane distances according to the focal length of the optics and the relative placement of the optics and the screen. The VPL Eyephone has a calculated virtual image plane distance at about 0.4 m with a distance of 16.4 mm between the optics and the screens [Robinett]. This places the convergence limits between 0.34 m to 0.48 m, a range which is good for close up work but not much else. Virtual Research gives similar figures for the distance to the image plane in their Flight Helmet. A graph (figure 13) shows possible virtual image plane distances that can be achieved with a LEEP optics system with a focal length of 20.7 mm. Similar graphs can be constructed for lenses of different focal lengths.

In a conversation with Eric Howlett of LEEP Systems, we obtained some optical specifications for their Cyberface. They said it has an interaxial optical spacing of 64 mm and an infinity point conjugate spacing, or parallax for images that appear to be at infinity, of 62 mm. He also said the focal length of the LEEP optics is 42 mm. The virtual image plane is calculated to be at about 2.1 m from the eyes. The minimum convergence distance is 1.1 m, and the maximum is about 25 m, effectively infinity. 1.1 m is still too great a distance to work with objects in the near field. In both the Eyephone and the Cyberface, the comfortable range of viewing distances is not sufficiently large for the anticipated manually interactive application in a VR scene.

Both LEEP Systems and Virtual Research indicated in private communication that they did not pay attention to the conflict in accommodation and convergence when designing their systems. The failure to do so inherently restricts the ability to present spatially correct images of the virtual world with these HMDs. Mark Bolas of Fake Space Labs said that they were still experimenting with where to put the image plane in their BOOM device. He said that in prototypes where the image plane distance was user adjustable, the user was unable to place it correctly. Because of the accommodation/convergence conflict, the particular application of VR will define an appropriate distance to the virtual image plane.

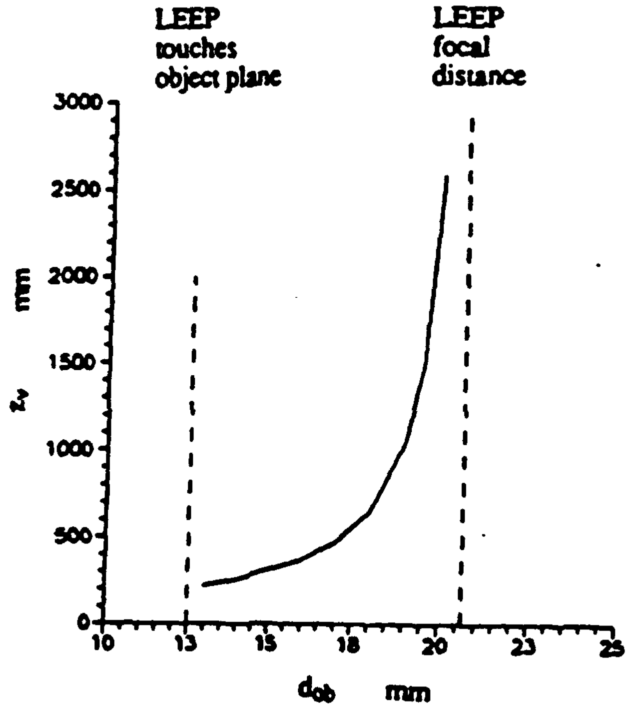

Figure 13. Distance Between Optics and Screen (D_{ob}) versus Distance to Virtual Image Planes (Z_V) for LEEP Focal Distance of 20.7 mm

3.2.7 Adjustable Elements for User Variations

Interpupillary Distance (IPD)

The IPD is a user specific characteristic, which should be taken into account in HMD design. As figure 14 illustrates, the IPD inherently affects the perception of depth. Each person perceives distance in relation to his or her own IPD and the subsequent angles for convergence of the eyes. Merely adjusting the IPD and not changing the parallax for each user will cause inaccuracies in the depth perception. The IPD should, therefore, be introduced in the graphics rendering model as a user specific constant [Robinett].

Infinity optics require an IPD adjustment since the small size of the exit pupil does not allow much translational movement of the eyes with respect to the optical axes of lenses. The VR Group HMD does have an adjustment, but it is somewhat difficult to use and get the correct binocular overlap [Veron, memo, 1992]. In general, inaccuracies in depth perception are possible if only the IPD is changed and not the parallax generated by the graphics workstation.

The LEEP optics of the Cyberface do not have an adjustable IPD, since the exit pupils are large enough to account for variations among users. This does not necessarily guarantee accurate depth perception, however. The Cyberface, by placing the infinity point conjugate spacing (parallax) of the images at slightly less than the interaxial spacing, ensures that the eyes will not have to diverge to fuse images. Again, neither the infinity optics nor the magnifier optics accounts for the IPD variation correctly.

Head Size

The different head sizes are easily accommodated by means of an adjustable strap. The way the helmet sits on the head, and thus the orientation of the tracker is a potential problem because it determines what image is displayed. Calibration techniques and procedures are required to remedy this situation.

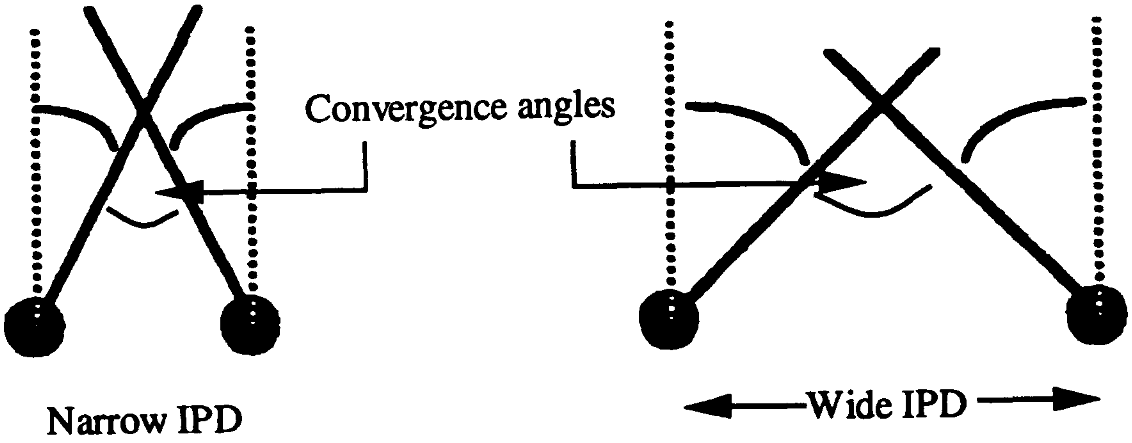

Figure 14. Eyes with Different IPDs Perceive the Same Object Distance with Different Convergence Angles

3.2.8 Physical Limitations

Weight

The weights of the infinity optics HMDs are usually greater than the weights of the magnifying HMDs. A CRT slightly smaller than 1 inch weighs between 3.5 and 6 ounces [Hughes]. Larger CRTs to increase the FOV are not a viable option because of the additional weight. A CRT with a screen size of 2.6 inches diameter weighs at least 1.5 pounds and is over 6 inches in length [Hughes]. The weight of infinity optics HMDs ranges from as low as 3 pounds in the VR Group HMD to as high as 6 pounds in other prototypes. The bulk of the CRTs contributes greatly to the moment of inertia and thus to user fatigue.

The LCD provides an obvious advantage in terms of weight, ranging from 80 g (2.8 ounces) for a 3-inch LCD to 180 g (6.3 ounces) for a 4-inch LCD [SHARP product bulletin]. The weight of an LCD-based HMD ranges from about 2.5 pounds to 3.7 pounds.

Mounting locations of the displays and optics is also a concern. Current CRT systems mount the CRTs on the side of the head, using relay optics to project the image to the eye. The optics add weight to the system. If the CRTs were mounted in front of the eyes, there would be too much weight on the face as well as an increase in moment of inertia of the system. A counterbalance placed at the back of the head further increases the moment of inertia. LEEP Systems use a front mount for the optics and LCDs. The weight is redistributed to the top of the head from the face by means of a counterweight. Experience has shown that this does not do enough to relieve the weight of the system.

The weight of current systems is still too great to permit comfortable use over an extended period of time. One viable alternative is mounting the display unit on a mechanical arm as in the BOOM. This allows the weight to be supported by the mechanical arm rather than the user's head.

Freedom of Movement

The HMDs can operate in 6 degrees of freedom because of the various tracking systems. The range of the tracker is currently limited to a circle of 5-foot radius from the source. The tethers needed to drive the electronics and the tracker not only contribute largely to the weight born by the user but also severely curtail the freedom of movement of the user.

Counterweights added to balance the HMD on the head contribute to the inertia of the unit. This decreases the ease with which the user can move around with the HMD and limits the positions that can be comfortably maintained.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

While HMDs are potentially the most effective means of providing a state of total immersion in VR, the effectiveness of the HMD is limited by the current state of display technology and the laws of physics. We find that HMDs fall short in the following areas:

1. ability to simultaneously achieve an image with a wide FOV, high resolution, and color;
2. achievement of an acceptable weight;
3. elimination of tethers;
4. range of visual accommodation; and
5. perceptual differences due to individual physiological characteristics (e.g., IPD).

A breakthrough in HMD technology is needed to make it a viable means for providing immersive VR. The present deficiencies in optical performance will not induce the user to sustain the inconveniences of the weight and tethers of either optical system. Further development of existing technology (e.g., increasing the resolution of miniature LCDs) may provide no more than incremental increases in the quality of the displays. Moreover, the small market demand for such technology is unlikely to warrant its development.

New ways of displaying VR in an HMD need to be pursued. Possibilities include the direct projection of an image onto the retina with a laser. It should be determined whether holographic optical elements, which have a greater degree of refractive ability, can provide significant advantages over existing HMD optical configurations. Projecting a real-time holographic image from an HMD by utilizing real-time holographic video techniques developed by MIT [Benton] should also be considered for immersive VR. The future of immersive VR depends on developing a method of displaying the images that can achieve the goals set forth in this document.

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APPENDIX A[1]

COMPUTATIONS CONCERNING EYEPHONE RESOLUTION

The low resolution Eyephone has 442 x 238 primary color pixels per eye. The total number of primary color pixels is 105,196. This means 35,065 triads, in an array that I am assuming is 256 x 137. The FOV for each eye is 86 degrees (horizontal) by 76 degrees (vertical). The total horizontal FOV is 108 degrees. The binocular overlap is 64 degrees.

Because of the assumptions made above, the following calculations are approximate. The total number of pixels (three color) horizontally is 256 x 108/86 (pixels per eye x total FOV/FOV per eye). This equals 321 pixels. The number of arc minutes per pixel horizontally is 108 x 60/321 or approximately 20 arc minutes per pixel.

The number of vertical three-color pixels is approximately 137. The number of vertical degrees is 76. This gives approximately 33 arc minutes per pixel vertically.

The same calculations, with the same assumptions, applied to the high resolution Eyephones gives the following results:

Total number of primary color pixels per eye is 345,600 in a 720 x 480 matrix. This gives about 416 horizontal by 277 vertical three-color pixels per eye. The horizontal FOV per eye is 86 degrees, and for both eyes is 106 degrees. The vertical FOV is 75 degrees. The total number of horizontal pixels is approximately 513 pixels. This works out to about 12 arc minutes per pixel horizontally. The number of three color pixels vertically is about 277. This works out to about 16 arc minutes per pixel vertically.

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[1] Dunn-Roberts, R., K. Uliano, P. Moskal, and M. Moshell, "Head Tracking and Head Mounted Displays for Training Simulation," Final Report, Visual Systems Laboratory Document VSLM92.4, Institute for Simulation and Training, University of Central Florida, IST-TR-92-12, 5 February 1992.