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A HELMET-MOUNTED VIRTUAL  
ENVIRONMENT DISPLAY SYSTEM

THESIS

Robert Keith Rebo  
Captain, USAF

AFIT/GCS/ENG/88D-17

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

**AIR FORCE INSTITUTE OF TECHNOLOGY**

Wright-Patterson Air Force Base, Ohio

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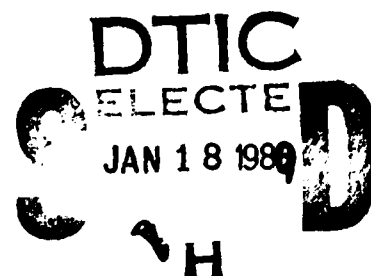
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DISPLAY SYSTEM

THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology  
Air University  
In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Computer Science

Robert Keith Rebo, B.S.  
Captain, USAF

December 1988

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## *Preface*

The purpose of this study was to research existing Helmet-Mounted Display (HMD) systems and develop a prototype version at the Air Force Institute of Technology (AFIT). This research is the beginning of continuing research into the design considerations and applications of HMD systems.

This study is divided into two parts. The first chapters outline the project and the research conducted. The last few chapters describe the design of the system and the results of experimentation using the completed system.

There are many individuals who deserve special thanks for their support during the research and development on this project. I am indebted to my thesis advisor, Major Phil Amburn for his relentless support and encouragement during this entire thesis effort. I would also like to extend a special thanks to my readers Dr. Matthew Kabrisky and Major John Stibravy for their guidance and timely suggestions. My gratitude also goes to Armstrong Aeromedical Research Laboratory for sponsorship of this effort.

Finally, and most importantly, I would like to express my deep appreciation to my wife and children for their understanding and encouragement during those long months spent at AFIT.

Robert Keith Rebo



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## *Table of Contents*

|                                         | Page |
|-----------------------------------------|------|
| Preface . . . . .                       | ii   |
| Table of Contents . . . . .             | iii  |
| List of Figures . . . . .               | vi   |
| List of Tables . . . . .                | vii  |
| Abstract . . . . .                      | viii |
| I. Introduction . . . . .               | 1    |
| 1.1 Background . . . . .                | 1    |
| 1.2 Problem Statement . . . . .         | 2    |
| 1.3 Assumptions and Design . . . . .    | 3    |
| 1.4 Scope . . . . .                     | 5    |
| 1.5 Methodology . . . . .               | 7    |
| 1.6 Equipment . . . . .                 | 9    |
| 1.7 Applications . . . . .              | 10   |
| 1.8 Summary . . . . .                   | 12   |
| 1.9 Chapter Overview . . . . .          | 12   |
| II. Historical Development . . . . .    | 13   |
| 2.1 Three Dimensional Display . . . . . | 13   |
| 2.2 The Helmet . . . . .                | 14   |
| 2.3 The Image Source . . . . .          | 15   |
| 2.4 The Display Optics . . . . .        | 16   |

|                                                         | Page |
|---------------------------------------------------------|------|
| 2.5 The Graphics Processor . . . . .                    | 17   |
| 2.6 The Position Tracker . . . . .                      | 17   |
| 2.7 The Kalman Filter . . . . .                         | 18   |
| 2.8 Summary . . . . .                                   | 20   |
| III. System Design Description . . . . .                | 21   |
| 3.1 Hardware . . . . .                                  | 21   |
| 3.1.1 The Helmet Mount . . . . .                        | 21   |
| 3.1.2 The LCD Displays . . . . .                        | 22   |
| 3.1.3 The Signal Converter . . . . .                    | 23   |
| 3.1.4 The Display Optics . . . . .                      | 26   |
| 3.1.5 The Polhemus Tracker . . . . .                    | 28   |
| 3.2 Software . . . . .                                  | 29   |
| 3.2.1 The Test Data Base . . . . .                      | 30   |
| 3.2.2 The Display Algorithms . . . . .                  | 30   |
| 3.2.3 Polling Algorithms . . . . .                      | 31   |
| 3.2.4 Polhemus Field Correction . . . . .               | 33   |
| 3.2.5 Predictive Tracking Using the Kalman Filter . . . | 36   |
| 3.3 Summary . . . . .                                   | 41   |
| IV. Results/Findings . . . . .                          | 43   |
| 4.1 HMD construction . . . . .                          | 43   |
| 4.2 RGB to NTSC Encoder/Convertor . . . . .             | 43   |
| 4.3 Display Program . . . . .                           | 44   |
| 4.4 Polhemus Field Correction . . . . .                 | 45   |
| 4.5 Predictive Tracking using a Kalman Filter . . . . . | 45   |
| 4.6 Tracker initialization . . . . .                    | 46   |
| 4.7 Images Displayed . . . . .                          | 46   |
| 4.8 Summary . . . . .                                   | 46   |

|                                             | Page |
|---------------------------------------------|------|
| V. Conclusions/Recommendations . . . . .    | 50   |
| 5.1 Possible Improvements . . . . .         | 50   |
| 5.2 Future Applications . . . . .           | 52   |
| Appendix A. User's Manual . . . . .         | 55   |
| Appendix B. Room Data Base . . . . .        | 57   |
| Appendix C. Polhemus Field Tables . . . . . | 67   |
| Bibliography . . . . .                      | 73   |
| Vita . . . . .                              | 75   |

## *List of Figures*

| Figure                                                          | Page |
|-----------------------------------------------------------------|------|
| 1. A typical display of a HMD system . . . . .                  | 4    |
| 2. The Sharp 3ML100 miniature LCD television . . . . .          | 7    |
| 3. The First Design of the AFIT HMD System . . . . .            | 8    |
| 4. The Basic Design of the AFIT HMD System . . . . .            | 9    |
| 5. Basic Kalman Filter Design (13:217) . . . . .                | 19   |
| 6. The Helmet mounted display System . . . . .                  | 21   |
| 7. Prototype HMD System mounted on an Aircraft Helmet . . . . . | 22   |
| 8. Three inch color LCD TV with extended cables . . . . .       | 23   |
| 9. Schematic Diagram of RGB to NTSC Convertor . . . . .         | 24   |
| 10. Angle of Diffraction . . . . .                              | 26   |
| 11. Shape of Uncorrected Polhemus Field . . . . .               | 34   |
| 12. Polhemus Field Vertical Correction . . . . .                | 35   |
| 13. AFIT HMD system, with front cover removed . . . . .         | 42   |
| 14. Room Database as Displayed on the HMD System . . . . .      | 44   |
| 15. An Airport Target in Mark Kanko's Threat Database . . . . . | 47   |
| 16. Flying Over a Digitized Terrain Map . . . . .               | 48   |
| 17. Examining a model of a DC-10 . . . . .                      | 48   |
| 18. A Three-Dimensional Floating Sphere . . . . .               | 49   |
| 19. Proposed New HMD Design . . . . .                           | 52   |



## *List of Tables*

| Table |                                                                   | Page |
|-------|-------------------------------------------------------------------|------|
| 1.    | Measured Polhemus position, direction, and twist . . . . .        | 67   |
| 2.    | Measured Polhemus position, direction, and twist (cont) . . . . . | 68   |
| 3.    | Measured Polhemus position, direction, and twist (cont) . . . . . | 69   |
| 4.    | Measured Polhemus position, direction, and twist (cont) . . . . . | 70   |
| 5.    | Measured Polhemus position, direction, and twist (cont) . . . . . | 71   |
| 6.    | Measured Polhemus position, direction, and twist (cont) . . . . . | 72   |

### *Abstract*

This effort researches existing Helmet-Mounted Display (HMD) systems and presents a prototype design of a color Helmet-Mounted Virtual Environment Display System. Many existing systems are discussed, including systems currently in use by the US Navy, Air Force, and Army. Several differing designs are presented and evaluated.

The Air Force Institute of Technology Helmet-Mounted Virtual Environment Display System places the user in an visual situation that is generated by a computer. This HMD system could easily be adapted for use with a video camera.

This paper presents an inexpensive system design that incorporates the benefits of other efforts. The cost trade offs are evaluated and the best design for the lowest cost is presented. The optics, three dimensional considerations, the mounting platform and display technologies are also discussed. The final HMD system design is described in detail and presented so that any reader could build a similar system for minimal cost. This system uses color Liquid Crystal Displays (LCD) mounted directly before the eyes of the user. Specially designed optics were developed to enable the user to focus on the image only inches away. The positional information of the user is determined by a sensitive electro-magnetic device developed by Polhemus Navigational Sciences. This system is very accurate but has a limited effective range. Predictive tracking is discussed and implemented using a simple Kalman filter equation.

The HMD system is designed to be mounted on any type of head gear. The system was mounted on both an aircraft helmet and an inexpensive bicycle helmet.

The goal of this effort was to build a simple, inexpensive color helmet-mounted display (HMD) system that places the user in a visual virtual world.

# A HELMET-MOUNTED VIRTUAL ENVIRONMENT DISPLAY SYSTEM

## *I. Introduction*

### *1.1 Background*

In a typical aircraft of today, a pilot might have to press several buttons before he sees a desired image on a cockpit display system, such as a radar. This system requires the pilot to look down into the cockpit to set and see the display. Whenever a pilot looks down into the cockpit, he must take his eyes off a potential target, and could lose sight of it. In a combat situation, losing sight of a hostile target could be fatal.

A current system that was designed to solve this problem is the Head Up Display (HUD). The HUD consists of an image projected onto a transparent screen situated directly before the pilot. The problem with the HUD is that it is situated only in front of the pilot. If the pilot turns his head, he can no longer see the HUD. The pilot will need to turn his head or move his eyes to see the HUD display and thus may lose track of the target. The HUD provides instrumentation needed to fly the aircraft as well as target acquisition information, allowing the pilot to fly the aircraft without having to look down into the cockpit. However, the HUD can't show all the available displays of a modern aircraft and doesn't follow the head movement of the pilot.

Armstrong Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, OH, is currently developing the concept of the Super Cockpit. The Super Cockpit is a futuristic aircraft cockpit that consists of many systems that enhance

the environment in which the pilot is flying. The systems in the Super Cockpit interact with the pilot and sense what the pilot is doing.

This thesis effort centers on the Binocular Display System portion of the Super Cockpit. In the Super Cockpit system, the display is mounted inside the helmet and will always be visible to the pilot. He will not need to look into the cockpit; the display will be directly before him when it is needed. The image that the pilot sees, as well as the buttons he needs to press, will appear directly before his eyes on a display mounted in his helmet. The pilot could reach out and press a button that exists in the virtual world only. The computer generates the virtual image, senses the pilot's hand position, applies pressure to his finger as feedback, and turns on the proper switch that corresponds to the button just "pressed."

## *1.2 Problem Statement*

The two current types of helmet-mounted systems that exist are the Helmet-Mounted Sight (HMS) and the Helmet-Mounted Display (HMD). The HMS is operational in many fixed wing and rotary wing aircraft. When in combat mode, a green gunsight appears on the visor of the pilot and all activated weapons will track with his head movements. Mounted in the helmet is a miniature monochromatic (green) Cathode Ray Tube (CRT). The Helmet-Mounted Sight is nothing more than a sophisticated gunsight that follows the movement of the helmet. Both the Army and Navy are currently using helmet-mounted sights (10:3).

A HMD system differs greatly from a HMS system. Whereas the imagery of a helmet-mounted sight system is a sophisticated gunsight, a helmet-mounted display can show any image which can be displayed on a CRT. It has the capability of displaying a wide field-of-view directly to the eyes of a user. A HMD can be used in many other applications.

In this effort, I propose to design and build a Helmet-Mounted Virtual Environment Color Display System that will place the user in a virtual environment.

This visual situation may be computer generated or simply a different view of his present situation.

### *1.3 Assumptions and Design*

The Navy uses a helmet-mounted display system developed for them that has a built-in laser projector system (1:242). The user sits inside a retro-reflective dome screen, then the image is generated and sent via fiber optics cables to the helmet. The image is then projected to the dome from the helmet. Such a system is usable only in a simulator environment and movement of the user is extremely limited (1:243).

A HMD system developed for the Air Force by Farrand Electronics consists of two miniature high resolution cathode ray tubes mounted in the bottom of the helmet (2:3). The Farrand VCASS system, as it is called, has two wide-angle monocular magnifiers that overlap in the center of the field of view. This system uses a patented "Pancake Window" wide-angle lens configuration to reflect the images to the eyes of the user (2:1).

However, all systems developed to date are monochromatic. An important factor is the use of color displays. All flight simulators use color images and yet all existing HMD systems use monochromatic line drawn images. These images, like that in Figure 1, are detailed but do not reflect the real world situation.

There are trade offs in any development; a HMD is no exception. A full color image would cause the wearer to become confused as he or she attempts to see two separate images at the same time (real world and displayed). In an overlay type of display, a line drawn image, as in Figure 1 would be useful and less confusing. However, to place the user in a visual virtual environment, a full color, shaded, filled in image is not only preferred but required.

The line drawn image does not look to the user like anything he has ever seen or ever will see in the real world, but a filled and shaded image looks similar to an image a user might expect to see in the real world. The line drawn images as in Figure 1 are

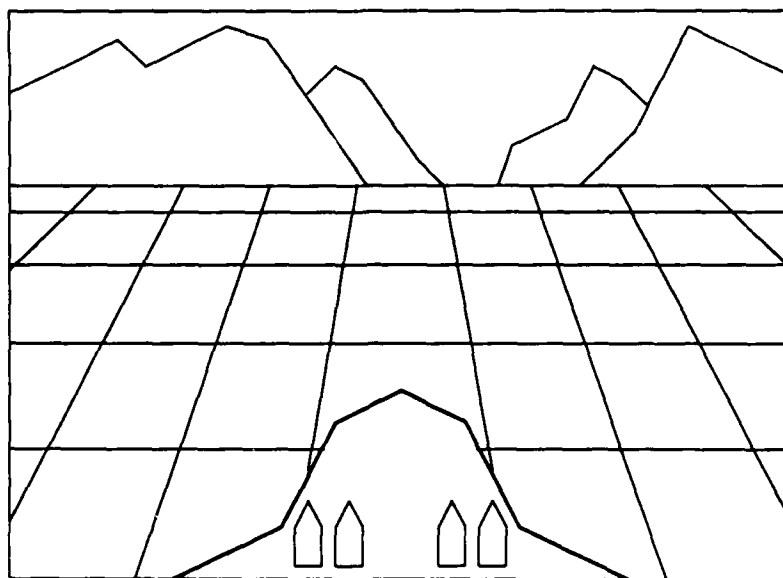


Figure 1. A typical display of a HMD system

the types of displays that pilots are expected to use and fly from. In discussing the problem with experts in the field and a manufacturer of HMD and HMS systems, it became apparent that the reason existing systems are all monochromatic is that all video sources in the cockpit are also monochromatic (24:1). However, color displays for the cockpit are currently under development and could be operationally tested in the very near future.

Research should not be limited to monochromatic displays. It is more desirable for the user to see a full color representation of the environment that closely resembles what he would expect to see if he were really in the simulated world. A full color display gives the user the ability to distinguish objects from one another, based on color. A color image is more believable to the user. A color image is more natural and greatly increases the user's perception that he is actually in the simulated environment. A shaded full color image also assists in depth perception and causes less strain on the human eye (7:185). A full color image is required to simulate reality in this application.

The AFIT HMD system is a helmet-mounted system with miniature LCD color displays that present a wide field-of-view image to the user. This system uses a magnetic position sensor to relay the helmet spatial orientation to the computer.

#### *1.4 Scope*

Monochromatic displays are easier to work with than color displays; the CRTs are smaller and the resolution is usually greater. Because the image is all one color, the CRT does not need to use the shadow mask technology needed to create a full color image. The color of the image depends upon the color of the phosphor used in the construction of the CRT.

A monochromatic CRT displays an image by using several scan lines. Each scan line is simply a trace of the electron beam as it travels across the face of the tube. As the intensity of the beam changes, the intensity of the displayed image changes also. A small separation between scan lines is usually visible but the picture appears to be continuous.

Almost all current color displays use some type of shadow mask technology. A shadow mask is dark screen with many small holes in it. Each hole has either a red, green, or blue phosphor in front of it. As the electron beam goes through the holes and strikes the phosphor at different intensities, varying colors of red, green, and blue are produced. The holes in the mask are extremely small and the images are typically viewed from some distance. This causes the colors to blend together and appear to be a single color.

A color image is essential if the goal of this effort is to simulate real world images. Simple line monochromatic images are excellent in some applications. If the image is to be used in combination with another image or the real world, a full color image could become very confusing. However, in order to place someone into a visual virtual environment, a full color image is essential. This effort is concerned with color images only and does not experiment with monochromatic image sources.

The AFIT HMD system places a person in a three-dimensional color virtual environment. To create the illusion of a three-dimensional image on a two-dimensional display, the system will rely on the cues that all people use when viewing images in three dimensions. After all, the human eye sees only in two dimensions (21:757).

A slightly different image is presented to each eye when testing depth perception. The human brain combines the images and interprets the difference as depth or distance. The presentation of different images to each eye to interpret depth is called stereoscopic viewing and is possible because human eyes are spaced about two and a half inches apart (7:52). However, stereoscopic vision is useless in moving environments and at distances greater than about 20 feet (7:53). As a typical person moves his head back and forth, his eyes do not focus on any single image long enough for his brain to interpret the distance. When this situation exists, other factors present the illusion of three dimensions to the brain. As the head moves, the brain uses kinetic depth effect or head motion parallax to see depth. Objects appear to move in relation to the objects behind them. Other cues for depth that are used are obscuration, in which closer objects cover further objects, or intensity cueing, where the color of distant objects appears to fade as if in fog. For example, distant mountains appear to be purple in color. Each of us uses all of these cues, as well as others, to determine depth in a three-dimensional view.

A Helmet-Mounted Display system can use all the cues for depth perception. The AFIT HMD system presents the illusion of three-dimensions by using all but one of the cues for depth. Because the primary use of this effort is in the visualization of time dependent data, that is moving images, stereoscopic views will not be presented. This will speed up the image refresh rate and enable the system to present a more believable image in real time. However, the system is designed so that future efforts could easily add this feature.

The image to be displayed could be a computer generated image from a database or from a remotely mounted or slaved video camera. The AFIT HMD



system uses a Silicon Graphics Iris 3130 Computer Graphics workstation to generate the image.

Systems that use fiber optic cables to transmit an image, generated nearby, to the helmet, limit movement of the head and do not allow the user to change his position. The AFIT system developed in this project provides a full circular field-of-view and the capability to look in any direction and see what would be seen if the user were actually in the simulated environment.

### *1.5 Methodology*

A primary factor in the design decisions for this system is the choice of a color display. Many displays were evaluated and a high resolution miniature Liquid Crystal Display (LCD) developed by Sharp Electronics was found to be the best suited for this application. The Sharp 3ML100 is shown in Figure 2. The reasons for this choice



Figure 2. The Sharp 3ML100 miniature LCD television

are explained in section 3.1.2. Several different system hardware configurations were tried. The first system actually designed is shown in Figure 3. This system proved to

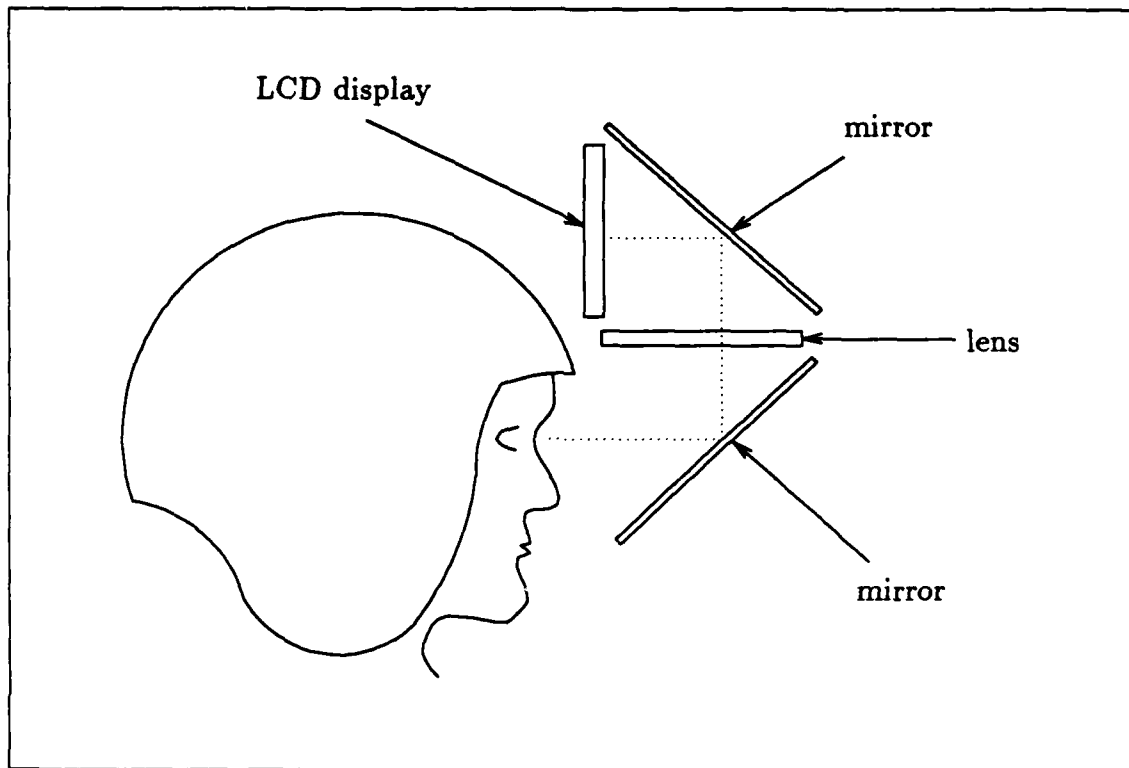


Figure 3. The First Design of the AFIT HMD System

be very heavy and awkward, so it was abandoned. The final design of the system is shown in Figure 4. The LCD miniature displays are mounted on a Plexiglas plastic frame that attaches to any helmet, including an Air Force aircraft helmet. The displayed image is then presented to the eye of the user through wide angle lenses that allow him to focus on an image only about two inches from the eye. The image appears to the user to be large enough to fill about a 70 degree horizontal field of view.

The Polhemus 3-Space tracker sensor is mounted on the top of the helmet. The source is suspended from the ceiling in the AFIT graphics lab. The tracking device reports to the computer the position and orientation of the helmet. The computer then has all the data necessary to calculate the proper image to display.

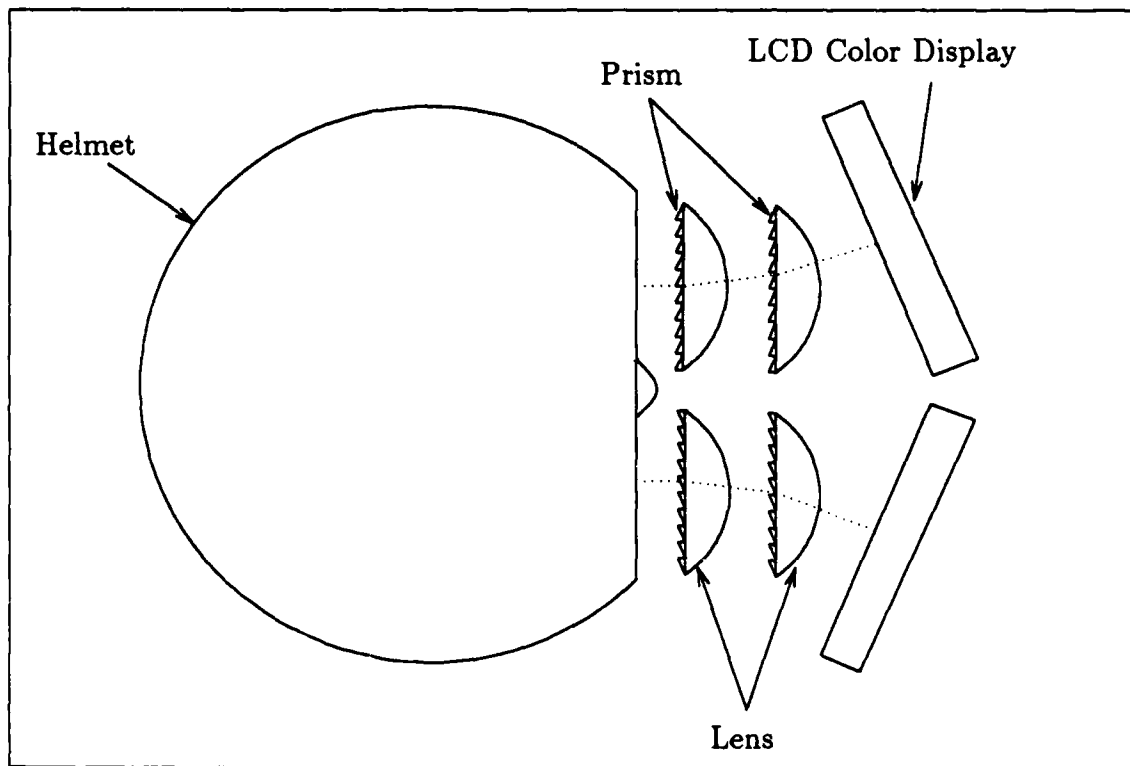


Figure 4. The Basic Design of the AFIT HMD System

Finally, after the assembly of the subsystems, and the test of its operation, the programs necessary to operate the system were written. The code is written in the C language on a Silicon Graphics Iris 3130 Color Graphics Workstation. Some of the source code was borrowed from the University of North Carolina at Chapel Hill and other portions were written by Phil Amburn and Gary Lorimor at the Air Force Institute of Technology.

### 1.6 Equipment

AAMRL provided some of the needed equipment. They provided a Polhemus 3-Space tracking device and built an RGB to NTSC convertor. The schematic design of this convertor is shown in section 3.1.3. Two aircraft helmets were provided by the 4950th Life Support Squadron at Wright-Patterson AFB, OH. The EENT clinic in the Wright-Patterson AFB Hospital donated ten and twelve diopter lenses. A bicycle

helmet and additional lenses were purchased to complete the equipment necessary to build and test the AFIT HMD system. Sharp loaned AFIT a miniature display to test. The display was more than satisfactory, so six miniature televisions were purchased. The system only requires two miniature television. The additional four televisions were purchased for spares and for the construction of a second HMD system.

A Silicon Graphics Iris 3130 Color Graphics Workstation, which was available in the AFIT/ENG Graphics Laboratory was used for the control and display in the system.

### *1.7 Applications*

An operational color Helmet-Mounted Display has many applications.

A Helmet-Mounted Display could be used in the area of Remote Robotic Telepresence. A current area of concern to the Air Force is the vulnerability of personnel on the ground during the refueling of an aircraft. In 1987, an AFIT graduate student demonstrated the feasibility of refueling an aircraft from inside a vehicle. An aerial refueling boom could be attached to a truck and the operator could successfully refuel the aircraft from the somewhat safer environment inside the vehicle. A Helmet-Mounted Display could be used to display the view from inside the vehicle and allow the operator to be physically in a safe bunker some distance away. A computer system could then control the image the operator sees. As the operator moves his head, the information would be sent to a remote video camera in the vehicle. The camera would be mounted on a motor driven platform and would move in the same manner as the helmet. The image from the camera would be sent to the helmet. The operator would then see the same image as if he were actually in the vehicle. The operator could control the entire refueling operation from a remote, safe position.

The uses of a HMD system in a flight simulator environment are virtually limitless. A HMD system would allow a pilot to be placed in any computer generated environment, allowing the simulation of almost any type of aircraft or flight conditions while only having to display the images at which the pilot is actually looking. This type of system would give the pilot an effective 360 degree view from the cockpit of any aircraft.

Another area of application that is of interest to the Air Force is that of motion sickness. Several students at AFIT have performed research in this area. However, none of the research at AFIT has explored the possibility of presenting conflicting information to a subject's eyes and ears. The human brain interprets motion by correlating information sensed from both the eyes and the ears. When these clues are unavailable, the brain tries to compensate, usually resulting in disorientation. A pilot experiences disorientation when flying through a cloud because there is no outside reference point and he or she must rely on the aircraft instrumentation (4). Using a HMD system, a volunteer could be placed in a chair, with the helmet on his head. The chair would begin to spin but the images the volunteer sees would remain stationary, directly in front of him. The results of such a test are not known at this time. Would the person develop motion sickness sooner, later, or not at all? Would the person become sick because he is moving or would his eyes override that feeling because he has a stable horizon to view?

As an extension of the previous application, consider G tolerant flying. If a pilot could lie down in a cockpit and still see straight ahead, by the use of a HMD, he could withstand very high G forces (4). If it is shown that a person could properly function in such an attitude with displayed images to look at, it may prove to be a useful future application of this system.

### *1.8 Summary*

Helmet-Mounted Display systems are an important technological step forward. The research done in this effort is limited to development of a system at AFIT. Future students may implement some of the applications that have been mentioned or even use the HMD system in other applications.

### *1.9 Chapter Overview*

This report is divided into five chapters. The first chapter has presented a brief introduction and overview of the problem. Chapter two is a review of the existing literature that discusses helmet-mounted display systems. Chapter three describes the design of the AFIT HMD system and the methodology that was used in the design and building of the system. Chapter four reports the findings of the project while chapter five reports overall conclusions and recommendations for future research.

There are three appendices to this report. The first is a simple user's manual for the HMD system and its associated software. The second is a listing of the room database used for testing and evaluation. The final appendix consists of tables of values that are used in the construction of the Polhemus field correction algorithm.

## *II. Historical Development*

### *2.1 Three Dimensional Display*

Many existing systems provide some cues of 3-D images. According to Gregory, a single human eye can only see two dimensions (7:50). The three-dimensional perception that one sees is a combination of several factors, which will be discussed later. A helmet-mounted display system possesses the inherent capability to display images that appear to be three-dimensional. A helmet-mounted display system consists of five main parts or functions: the helmet, the image source, the display optics, the computer, and the position tracker.

A three-dimensional HMD system presents to the user a perspective image which changes as he moves. Ivan Sutherland has shown that suitable two-dimensional images can be displayed directly to the eye of the user, thus creating the illusion of three dimensions (21:757). Some of the visual cues that provide each person with three-dimensional views of the world are:

1. Stereoscopic vision. The viewer receives a slightly different image to each eye. Gregory states that the brain interprets the difference in these images as depth (7:52).
2. Kinetic Depth Effect. The change in the image as a person moves his head causes objects closer to the observer to appear to move faster than those more distant. This effect has been called "head motion parallax" by Gregory and Holloway, and has been the subject of intense research (7:182).
3. Shading and Shadowing. The way light falls on an object is an indication of the objects' shape and orientation (7:185).
4. Intensity depth-cueing. Objects that are further away appear dimmer, as if in fog (9:7).
5. Obscuration. Closer objects obscure or cover up further objects (7:182).
6. Perspective. This is the non-parallel view of a parallel object (9:7).

A pioneer in computer graphics, Ivan Sutherland is quoted as saying:

Although stereo presentation is important to the three-dimensional illusion, it is less important than the change that takes place in the image when the observer moves his head. The image presented by the three-dimensional display must change in exactly the same way that the image of a real object would change for similar motions of the user's head. Psychologists have long known that moving perspective images appear strikingly three-dimensional even without stereo presentation [20:757].

The usefulness of a complicated stereographic system was evaluated by researchers at Honeywell Avionics Division on contract with the Flight Dynamics Laboratory. The researchers concluded that "there seems at the moment little advantage for a more complicated visually coupled stereo system" (18:49). They did however state that "stereographic representation of tactical combat scenarios are viable displays" (18:49). However, only stereographic systems were even evaluated. Systems that do not present a stereo image were not evaluated. Current research tends to forget that the human eye can only determine depth from a stereographic image when the images to be discerned are less than about 20 feet away (7:53). This is usually not the situation in an aircraft environment.

There are several true 3-D display systems. However, the HMD is one of the only display systems that presents an image to the user relative to his head position. This being so, the HMD is able to take advantage of this most powerful cue for depth, the "kinetic depth effect."

## 2.2 *The Helmet*

The HMD system requires a stable mounting platform. Several different configurations for mounting head-mounted displays have been tested. Fisher, from NASA, developed a system that mounts on a motorcycle helmet (5:78-79). The University of Utah developed a system that used a head set and harness to hold the head-mounted display system (23:5). The University of North Carolina at Chapel Hill developed



a system that attaches to a "hat band" (9:23). The US Military is experimenting with systems that mount on aircraft helmets (1:251).

A helmet-mounted configuration is practical and advantageous. It provides a stable platform for mounting the display system and allows the system to be mounted lower, thus lowering the center of gravity on the head. However, a helmet is heavy and can cause neck fatigue over prolonged use.

### *2.3 The Image Source*

Breglia states that the most common image source in HMD systems is the miniature cathode ray tube (CRT) (1:245). The system developed by Vickers at the University of Utah uses two miniature CRT displays (23:10). Other systems, such as those developed by NASA and UNC, use miniature LCD displays (5:78-79; 9:22). The system developed by CAE Electronics uses fiber-optics to transmit an off-the-head graphical image to the eyes of the user (3:2,7). Helmet-mounted laser projectors have also been used by the Air Force Human Resources Laboratory to project the desired image to a dome screen rather than directly into the pilot's eyes (1:246). This laser projector system requires no beam splitters and permits a very wide field of view but can be used only in a restricted environment.

Research and testing have concentrated on the use of monochromatic displays. Possible reasons that color has not been used are the unavailability of a suitable miniature color CRT and the poor quality of existing color LCD displays. In a recent letter from Elbit Computers, a leading manufacturer of HMS and HMD systems, Wiener says:

However, our display is monochromatic, using a 1/2" CRT mounted on the helmet. We do not have a colour CRT that is suitable for a helmet mount. Nor do we consider it essential - since all possible video sources in an aircraft are monochromatic, anyway [23:1].

In order to present an image to a user that appears real and to take advantage of all the cues of a 3-D view, a color display is essential. Intensity depth cueing, shading and shadowing can best be shown in a color display.

In 1978, Westinghouse R&D Center developed a thin film transistor (TFT) LCD display that provided high resolution in a monochromatic display (22:1-2). This technology was adapted by Sharp Electronics and others to develop a high resolution color LCD display (19:1). Using a high contrast black matrix, the Sharp LCD color display provides 92,160 dots of resolution, which is about half that of a typical television (19:2). It appears that such a display would be suitable for use in a HMD system.

#### *2.4 The Display Optics*

The optics in a HMD system provide the pathways for the image to be displayed to the user's eyes. There are several possible mounting configurations each requiring different optics.

Some systems, like the NASA system, have simply mounted the display out in front of the helmet, enabling the user to look through wide-angle optics directly at the display (5:78). The University of Utah's system reflects the generated image from the side of the user to an eye piece (23:10). The University of North Carolina's system uses optics and mirrors to reflect a display that is mounted in front of the user's forehead to the eyes (9:22). The primary concerns in designing optics for a HMD are the effective field of view and the weight. In order to simulate a view into the real world, the generated image must be large enough to present a wide field of view display to the user's eye. However, this necessitates larger optics and thus more weight. If the image is large enough to fill the majority of the user's view, say 60 to 90 degree horizontal field of view, the user begins to picture himself or herself actually in the displayed environment.

## *2.5 The Graphics Processor*

All the HMD systems discussed so far have used a general purpose computer to interpret head position information and generate the image to be displayed (9:14,25). A system must calculate color shades and shadows fast enough to appear real, which requires about thirty images per second. However, the current state of technology does not allow for the generation of shadows in real time. Those systems which do display shadows only use fixed darker polygons to simulate the shadow. A general purpose computer is not designed for this purpose and generally cannot calculate the complex graphics calculations fast enough. It is a requirement to use a very fast and expensive processor or one that has special purpose hardware to do the graphics calculations (9:40). With the development of the graphics workstation in recent years, such a machine is available.

## *2.6 The Position Tracker*

The tracker is the part of the system that reports the current position of the user. The tracker must report the movement of the head as soon as it moves, thus allowing the image to be updated to match the new head position.

Many different tracking systems have been tried. One prototype of a head-mounted display system used a mechanical head position sensor (3:2). Sutherland also tried a mechanical system and used a mechanical arm hanging from the ceiling which rotated about pivots in its ceiling mount (21:759-760). The position of the pivot joints were measured and sent to the host computer. He also tried a continuous wave ultrasonic position sensor (21:760). Vickers at the University of Utah also used a mechanical system (23:12).

With the development of the Polhemus 3-Space Tracker, a lightweight, accurate position tracker was made available for widespread use. This tracker is being used by both NASA and UNC (5:80; 9:29-30). The Polhemus tracker system generates a magnetic field which is sensed by the passive tracker on the helmet. The system

then reports the position of the sensor with remarkable accuracy. This system is used to track head position as well as hand position by NASA (5:80).

## *2.7 The Kalman Filter*

The US Air Force Human Resources Laboratory has investigated the problem of display lag time in HMD systems. They deemed it necessary to implement some kind of position prediction scheme (20:2). The first type of prediction system they used was an algorithm based on previous head position. They then used an algorithm that incorporated velocity (20:4).

The simplest way to predict head position is to extrapolate the current position using a constant velocity (11:14). However, head movement does not exhibit constant velocity (20:2). The next approach was to integrate an accelerometer into the system. Three linear accelerometers were mounted on the helmet and were used to read head acceleration information. This information along with the position information was used to predict the next head position (11:16).

Other weapon systems must also predict future events without the benefit of accelerometers. The US Air Force has used Kalman filters in a variety of applications. The application that is of particular interest to this effort is the use of a Kalman filter to keep a laser beam on a moving target. Basically, the filter must predict the location of the moving target in order to keep the beam focused on a constant point on the target. This predictive nature of the Kalman filter can be used to predict where a viewer will be looking using a Helmet-Mounted display.

A Kalman filter is a recursive algorithm. The filter is recursive in nature in that it uses a feedback loop to compare its output, a state estimate, with the next input measurement (13:217). A simplified diagram of a Kalman filter is shown in Figure 3.

$K$ ,  $H$  and  $\Phi$  are matrices that define the characteristics of the filter. The dimensions of the matrices are determined by the number of input variables, and

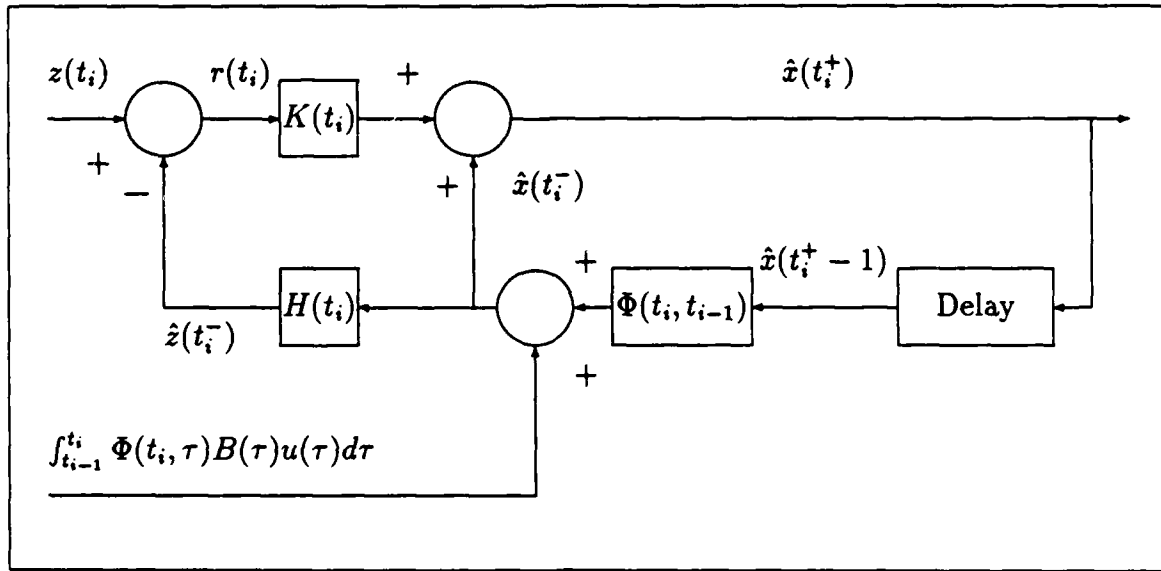


Figure 5. Basic Kalman Filter Design (13:217)

thus the number of states in the filter. The  $K$  matrix defines the gain of the Kalman filter. The  $H$  matrix defines the measurement model characteristics. The  $\Phi$  matrix identifies the dynamics of the filter. The filter can be tuned to produce the desired output by adjusting the  $Q$  and  $R$  matrices that are used in determining the  $K$  matrix. The initial measurement  $z(t_i)$  is the input at time  $t_i$  (13:217). The value  $\hat{x}(t_i^-)$  is the propagation of the optimal estimate,  $\hat{x}(t_{i-1}^+)$  by the filter. The estimate is used to compute  $\hat{z}(t_i)$  which is a prediction of the measurement at time  $t_i$ . The difference between the estimated value  $\hat{z}(t_i^-)$  and the next actual measurement  $z(t_i)$  is the residual and is identified by  $r(t_i)$ . This residual "is then passed through an optimal weighting matrix  $K$ , and used to update  $\hat{x}(t_i^-)$ , the best prediction of the state at time instant  $t_i$  before the measurement is taken." (8:27)

This filter can be used to predict the position and orientation of the head, where the tracker is mounted. The actual measurement from the Polhemus device is the input or  $z(t_i)$  of the filter. The  $\hat{x}(t_i)^+$  is the best estimate of the state vector  $x(t_i)$  after the Polhemus measurement data is received. However, the  $\hat{z}(t_{i+1}^-)$  is the best estimate of the next position. This can be used to draw the image before the

person is looking at that position (15). This application will reduce the lag time or "jerky" behavior of the displayed image.

## *2.8 Summary*

Helmet-Mounted systems have been under investigation for quite a few years. They are extremely desirable because they provide many of the most important cues needed to give the illusion of a three-dimensional computer generated world. A helmet-mounted display system allows the user to view a computer generated image in the most natural fashion, through head motion. In most systems, if the user wishes to look left right, up or down, the motion is accomplished through the movement of a mouse or a joystick. The HMD system follows the movement of the head. Therefore to look left, right, up or down the user must simply do so.

The systems researched in this effort are all monochromatic with no plans to use color. Color displays are available and have definite disadvantages. Color displays, for example, do not have the resolution of monochromatic displays. However, the use of color enables the presentation of more believable images. The user of a full color HMD system can feel he has been placed in an virtual visual environment. The AFIT HMD system, as described in the following chapter, uses full color displays to present a three-dimensional image to the user.

### III. System Design Description

#### 3.1 Hardware

The Helmet mounted display hardware consists of four parts. Each part of the overall system will be described in detail. Figure 6 shows the basic configuration of the Helmet-Mounted display as it has been designed.

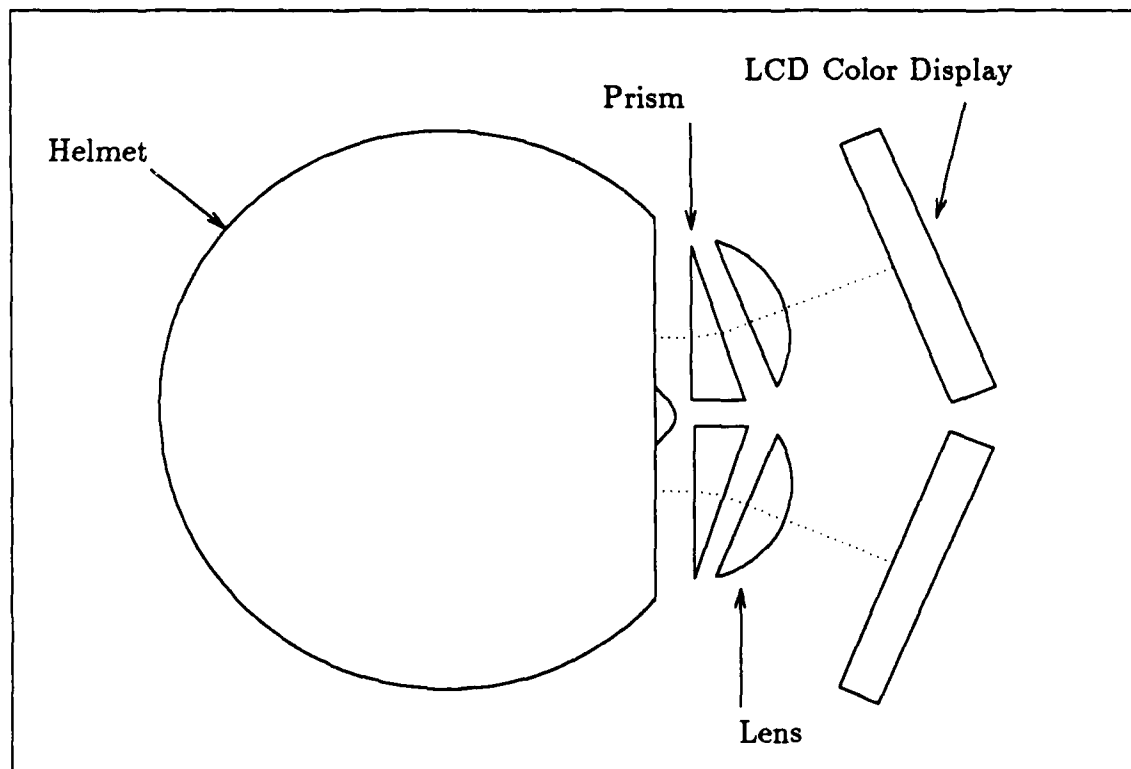


Figure 6. The Helmet mounted display System

*3.1.1 The Helmet Mount* The helmet-mounted display system may be attached on an aircraft helmet, a motorcycle helmet, a bicycle helmet, or any other head gear that will support the display system mount.

The display system mounts on a U shaped bar of plastic. The bar mounts to the helmet by the use of two thumb screws attached to a mount at the user's

temples. Figure 7 shows the HMD system without covers in use mounted on an aircraft helmet. The center of gravity of the system is such that it is not heavier on



Figure 7. Prototype HMD System mounted on an Aircraft Helmet

any side, front or back of the device. The electronics that drive the LCD displays are mounted on the ring and can slide fore or aft. This adjustment is provided to allow easy control of the center of gravity.

*3.1.2 The LCD Displays* The liquid crystal displays (LCD) are the Sharp 3ML100 three inch color televisions. They are relatively inexpensive (suggested retail of about \$400) and readily available. Several other display systems were evaluated. The Sharp systems presented the best resolution currently available in a miniature color display. Many aspects of a CRT make them more desirable, such as resolution and brightness, but their weight, size, heat and power requirements make them unsuitable for a helmet mounted system. Figure 8 shows a modified television.



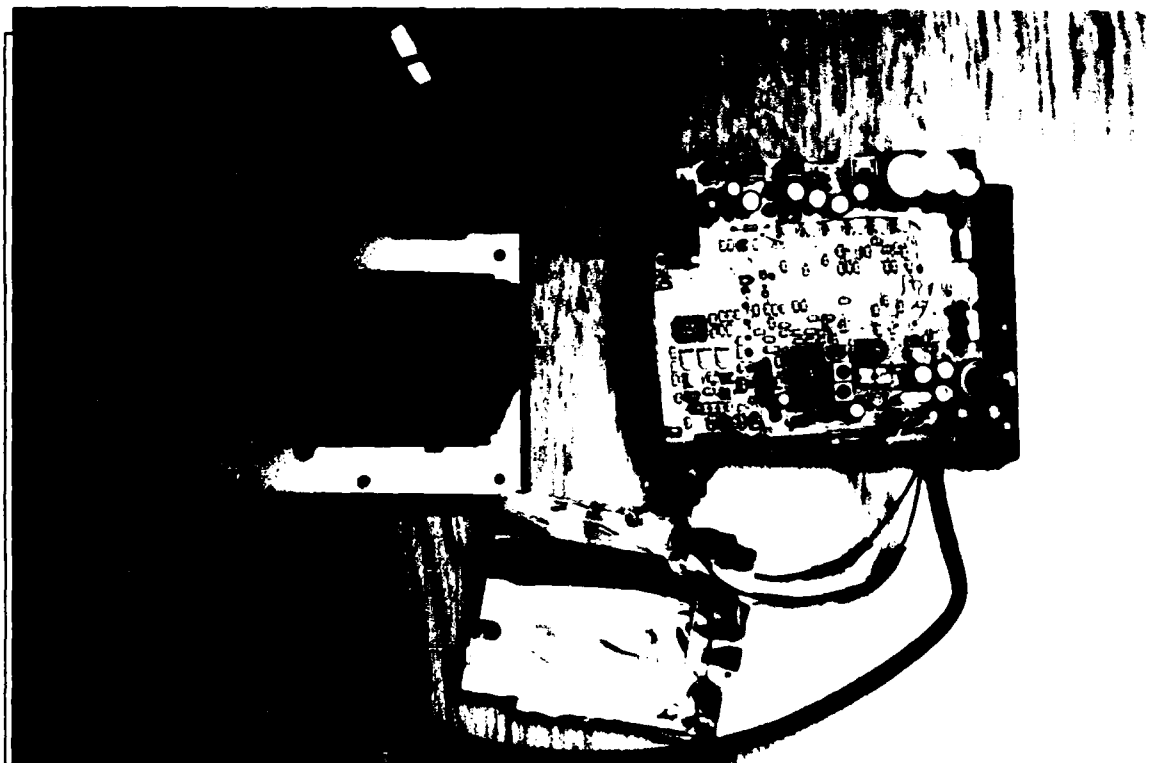


Figure 8. Three inch color LCD TV with extended cables

This modification was accomplished by AFIT Engineering Lab personnel and me to allow the display screen to be 18 inches away from the electronics. The fluorescent backlight circuitry and the 14 connector ribbon cable leading to the LCD display were extended 18 inches by Mr. Orville Wright of AFIT/ENG. I made the modifications to the television casings and the fluorescent backlight system.

*3.1.3 The Signal Converter* The RGB to NTSC convertor used in the beginning of this project was designed and built by technicians at Armstrong Aerospace Medical Research Laboratory. The convertor is based on the Motorola MC1377 integrated circuit. The schematic diagram is shown in Figure 9. The system accepts inputs from 75 ohm cables, using BNC connectors. The input signals are red, blue, green and sync. This convertor expects the signals to be in a 512 by 512 format. It does not convert a high resolution RGB signal to a low resolution NTSC signal.

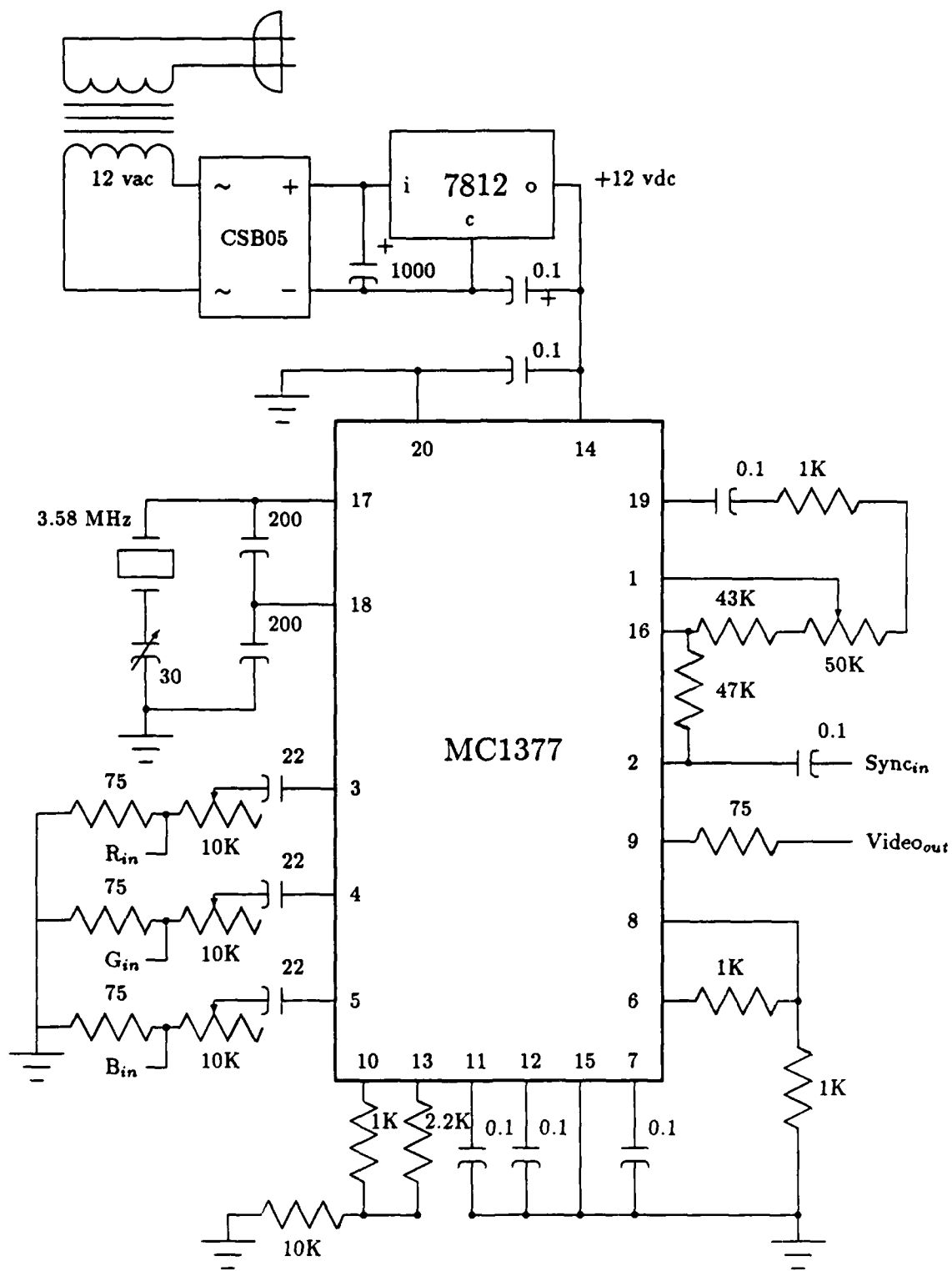


Figure 9. Schematic Diagram of RGB to NTSC Converter

The Silicon Graphics workstation can be run in an NTSC mode. When the Silicon Graphics is used in the NTSC mode, the signals on the R, G, B and Sync output lines are compatible with this convertor. The R, G and B inputs of the convertor have in-line variable resistors to allow adjustment of the colors. The overall color is also adjustable. This system is extremely low cost and the results are acceptable but not as good as would be possible with a higher cost system. A much more expensive converter, the Lyon Lamb ENC VI Color Encoder/Sync Generator was purchased. This new system arrived in October 1988 and was first used in a demonstration for the AFIT/CC in October 1988. This encoder or convertor performs the same function as the one used previously but greatly increases the quality of the displayed image!

A JVC BY-110 professional quality video camera was also used to convert the displayed image into a NTSC video signal. This camera was placed on a tripod directly in front of the Silicon Graphics display. The resulting picture was better in some aspects and not so good in others. The advantages and disadvantages were found to be as follows.

Advantages of using a video camera:

1. Better range of colors
2. Straight lines, no stair stepping of the lines
3. Better control of the image to be displayed

Disadvantages of using a video camera:

1. Color wash out due to room lighting and poor contrast
2. Must be mounted directly in front of display, hampering access to the terminal
3. Reflections off the screen can be seen in the displays
4. The image has a "fuzzy" appearance

The camera, although it eliminated the stair stepping of diagonal lines, was not a good alternative to using a convertor. The good clear colors and the absence of reflected images made the convertor the better medium for displaying the image. The inexpensive convertor described above does not reproduce the exact colors sent by the graphics workstation. The Lyon Lamb convertor does, however, produce an almost perfect converted image.

*3.1.4 The Display Optics* The lenses and prisms for the system were designed with help from the Wright-Patterson Air Force Base EENT clinic and Bell Optical in Dayton Ohio.

Three different powers of lens magnifications were used during testing. In combination with these lenses, a variety of optical prisms were available to experiment with. The layout of the system is shown in Figure 10. The first sets of optics used

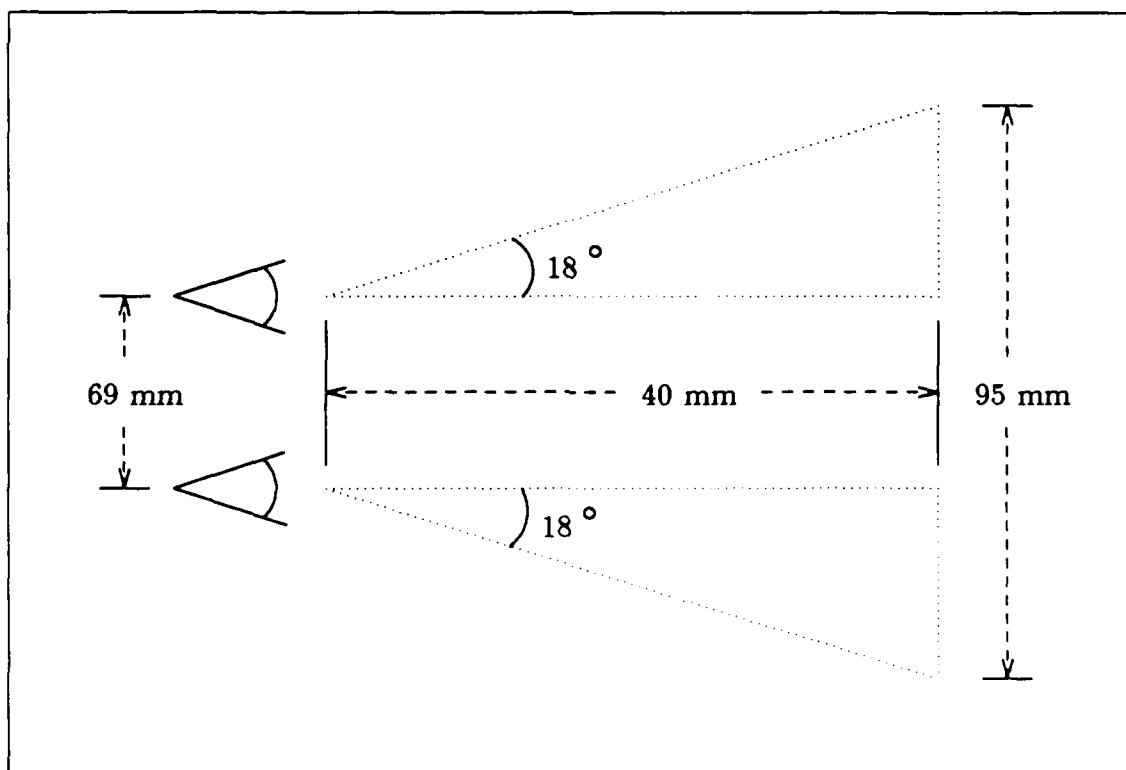


Figure 10. Angle of Diffraction

were, +15 diopters with 15 degree prisms, +20 diopters with 20 degree prisms, and +22 diopters with 25 degree prisms. Also, 30 and 7 degree prisms were available. Using a focal length of 40 mm, a distance between pupils of 69 mm, and a minimum distance between centers of the LCD TVs of 95 mm, the required angle of diffraction (AoD) was calculated to be about 18 degrees.

The equations and calculations for the Angle of Diffraction (AoD) are shown in the following equations:

$$AoD = \frac{EFL}{\sqrt{(\frac{OD-PD}{2})^2 * EFL^2}} \quad (1)$$

$$\cos(AoD) = \frac{40mm}{\sqrt{(\frac{95-69}{2})^2 + (40mm)^2}} = .9510 \text{ therefore } AoD = 18.0^\circ \quad (2)$$

However, the effective diffraction angle of the press on prisms was less than the rated angle. This may be due to the lenses in the system. Experimentation showed that the best optical characteristics of the system are as follows:

1. Effective focal length (EFL) = 40 mm
2. Pupil distance (PD) = 69 mm
3. Description of lens = + 22 diopters
4. Angle of diffraction (AoD) = 45 degrees
5. Individual horizontal field of view = 60 degrees
6. Individual Vertical field of view = 50 degrees
7. Overlap = total

*3.1.5 The Polhemus Tracker* The Polhemus 3-Space tracker uses low frequency, magnetic field technology to determine the position and orientation of a sensor in relation to a source or other specified frame of reference; providing a full six degrees-of-freedom measurement (16:1-1). Some difficulty was experienced with reliability of the Polhemus 3-Space tracker. The tracker system consists of three parts: one or two sources, one to four sensors, and a system electronics unit (SEU) (16:2-12). The source is a set of three magnetic field coils, each in a different plane of orientation.

Warren Robinett, formerly of NASA Ames, said that the Polhemus sensor is extremely susceptible to interference from metal of any kind (17). The 3-Space User's Manual emphasizes that the source and the sensor must be mounted on non-metallic surfaces with nylon or plastic screws (16:2-13). In fact, it goes on to say that "large metallic objects such as steel desks, bookcases, and metal walls should be at least six 6 feet away from the source (or sensor)" (16:2-13). The User's Manual recommends that the source be attached to a "non-metallic mount (wood, plastic, etc.)" (16:2-14). Therefore, the source was mounted on a plastic bar suspended from the ceiling. The source was suspended approximately 30 inches from the ceiling, and about seven feet from the floor.

The sensor was mounted on the front part of the HMD system. This proved to be a major problem because the LCD TVs are mounted in a metal bracket. The design had to be changed to mount the sensor on the top of the helmet, using velcro. After mounting the Polhemus sensor away from the metal in the LCD displays, few problems were experienced with the accuracy of the device. The accuracy, however, decreases as the wearer moves farther from the source. For maximum accuracy, the sensor should not be more than about  $\pm 10$  inches in X and Y, and +16 inches in Z from the source (16:2-11). The Polhemus sensor is accurate to 30 inches and less accurate up to a maximum of 60 inches from the source (16:1). The primary contributor to the inaccuracy of the device was found to be the shape of the magnetic

field (see section 3.2.4 for more information). Any metal, including aluminum, in or near the field will warp the rectangular shape of the field. The Polhemus report becomes quite inaccurate as the sensor approaches its maximum range. In an enclosed environment, such as a cockpit, the Polhemus tracker is very accurate provided that the variations in the magnetic field are corrected in the software.

### 3.2 Software

An existing program, *bspview.c*, based on the BSP display algorithm was used (6:66). This program was modified to read the input of the Polhemus tracker and the mouse. The routine was then modified to display a room data base in a fully interactive environment. The room data base is described in section 3.2.1. The system now places the user into any visual environment, depicted by a BSP tree representation. Because of the extensive rework involved, the program was renamed to *display.c*.

In order to use the *display* program, the database must be in a binary BSP tree format. For additional information on the use of the system, see Appendix A.

*Display* is used to view a BSP tree, and the mouse is used to move forward, backward, and to reset the scale and position. The directional information is taken from a sensor on the top of the helmet. Wherever the wearer looks, he will see the image in that direction and will travel in that direction by the use of the mouse. A help menu is available. It lists all the available options in *display*, and is the first screen displayed. *Display* will run on the Silicon Graphics Iris 3130 workstation in either NTSC or 60Hz mode. The software defaults to the NTSC mode.

*Display* reads the binary BSP tree from a file and reads viewing parameters from standard input. *Display* also reads in the Polhemus field correction data from a file *field.dat*. The field correction algorithm is explained in section 3.2.4. This data file is actually read during the correction initialization routine in *correct*.

The system is designed to run on the SG Iris 3130 and minor software modifications would be necessary in *initpol.c*, *bsp.c* and *graphics.c* to port the system to another workstation.

**3.2.1 The Test Data Base** The data base created for the testing of the system displays the room in which the Polhemus tracker source is mounted. The data base consists of a file called *roomDB.new*. The file consists of 236 points that form 59 rectangular polygons. The file contains the *x*, *y* and *z* values, along with the color and normal information for the objects represented. A complete listing of the data base is in Appendix B.

A similar room data base was created that had several floating cubes at 68 inches off the ground. This file was used for the calibration of the Polhemus system.

Both data files contain comments. The comments are on separate lines, prefaced by a percent sign (%). These special characters are not recognized by any of the programs. Therefore, a short program had to be written to delete any comment lines in the input file before converting it to BSP tree format. A script file, called *new2bsp*, was written to do just that. It takes an AFIT polygon file, with comments, deletes the comments, and converts the polygons to BSP tree format. This conversion is done by the script program running another program called *new2old*. This program creates a file of polygons in UNC polygon format. This older style of data file is then used by another program, *treemaker*, to create a binary BSP tree representation of the room data base.

**3.2.2 The Display Algorithms** This system uses an implementation of the BSP tree traversal algorithm with the input values being read from the Polhemus 3-space tracker and the mouse. The original code was developed by Eric Grant and Greg Abram at the University of North Carolina at Chapel Hill. At UNC, this code was used with a Vax 11/780 and an IKONAS frame buffer. Only a few changes were required to make this run on the Silicon Graphics Iris 3130 workstation, principally



in the interface to the graphics routines. These changes were made by Phil Amburn at the Air Force Institute of Technology in August 1987.

*3.2.3 Polling Algorithms* The system initializes the Polhemus 3-Space tracker using the commands as outlined below.

To open the Silicon Graphics communication port to the Polhemus tracker, the following sequence is used.

```
path="/dev/ttyd2";
oflag = O_RDWR | O_NDELAY;
if ((fd = open(path, oflag)) == -1)
    printf("Cannot Open Polhemus!\n");
```

The communication port is set up for hang up on last close, eight bits, 19200 baud, local line, enable receiver, enable signals and canonical input using the following sequence of statements.

```
cbreakTTY.c_cflag = HUPCL | CS8 | B19200 | CLOCAL | CREAD;
cbreakTTY.c_lflag = ISIG | ICANON;
ioctl(fd, TCSETA, &cbreakTTY);
```

The next set of statements is used to boresight the Polhemus to the default boresight. This also configures the Polhemus for an increment of 0, to output ASCII data in non-continuous data transmission mode, and sets the distance units to inches.

```
strcpy(buffer, "b1\rI0\rFcU");
write(fd, buffer, strlen(buffer));
```

The next statement defines the maximum and minimum X,Y,Z values to be used by the Polhemus device.

```
strcpy(buffer,"V1,65,65,65,-65,-65,0\r");  
write(fd,buffer,strlen(buffer));
```

The operational hemisphere of the magnetic field produced by the source must be defined to the Polhemus. This is set to have the zenith on the X-Axis with the next statement.

```
strcpy(buffer,"H1,0,0,1\r");  
write(fd,buffer,strlen(buffer));
```

Set the Polhemus to send back the position in cartesian coordinates (X,Y,Z), the direction cosines, and the twist about the line of sight axis. These are needed for the HMD system. The Polhemus report is then followed by a carriage return and a line feed.

```
strcpy(buffer,"02,5,4,1\r");  
write(fd,buffer,strlen(buffer));
```

After initialization of the Polhemus, it is necessary to start the system. This next sequence sends out an initial poll to the Polhemus.

```
ioctl(fd,TCFLSH,0);          /* flush the buffer */  
write(fd,"P",1);             /* poll the Polhemus */
```

Lastly, this next sequence of code will read the Polhemus data and put it in variables for later use.

```

numbytes = read(file_des,buffer,SIZE);
sscanf(buffer,"%2c %f %f %f %f %f %f %f %f %f ",
        non,&tx,&ty,&tz,&tpx,&tpy,&tpz,&tmp,&tmp,&ttw);

```

The code needed to use the Polhemus 3-Space tracker is not that difficult. However, as is the case with many User's Manuals, the 3-Space User's Manual lacks useful examples and the user is left to his own devices to figure out how to use the system (16). Captain Gary K. Lorimor spent many evenings reading the User's Manual and trying different combinations to achieve the desired results. I am indebted to his efforts for the quick progress on this project.

*3.2.4 Polhemus Field Correction* The Polhemus 3-Space tracker is quite accurate. However, the system is very sensitive to metal interference (17). It is very critical to not position any metal between the Polhemus source and the source on the helmet. The sensor should not be mounted near any metal. As mentioned before, the Polhemus was very accurate when the sensor, mounted on the helmet, was not mounted near any metal and was positioned not more than about 30 inches from the source. Beyond this distance, the magnetic field is no longer orthogonal. The approximate shape of the field is shown in Figure 11. Since the user may be more than 20 inches from the source, a position correction algorithm had to be used to allow the wearer to walk around the room and to present a proper image to the him as he moves away from the Polhemus source.

A short routine was added in the *display* program to read the mouse button. If the center button was pressed, the program would print out the current position, direction, and twist information. With the helmet-mounted display system on my head, I walked through the magnetic field, stopping at the markers set in the room database. I then stood erect and pressed the mouse button. The vx, vy, and vz values output by the program segment are the current position values. The px, py, pz are the current direction cosine vectors. The twist is the measured rotation angle

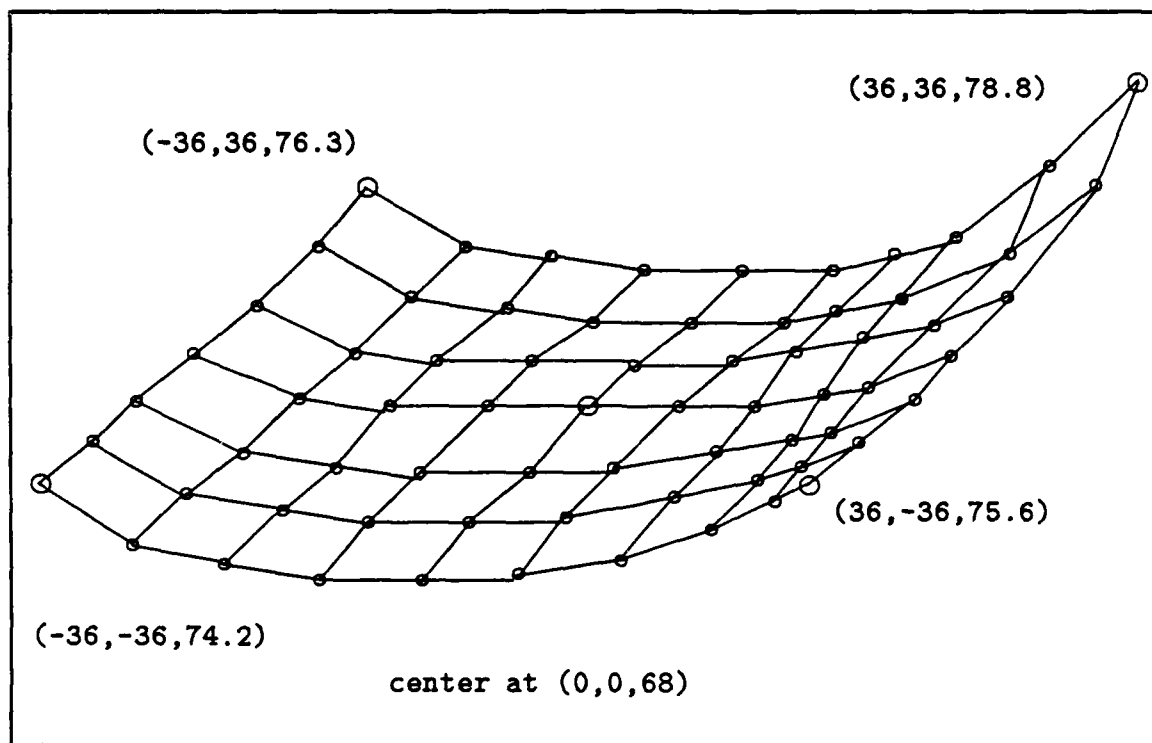


Figure 11. Shape of Uncorrected Polhemus Field

about the current line of sight. These values are the actual values reported by the Polhemus and corrected for the Polhemus source orientation. The data collected from this program was saved in a script file. Lastly, values were added to the file that exceeded the range of the Polhemus to insure that a lookup into the table would not fail. Tables 1 through 6 in Appendix C show this data.

The data collected from the X and Y values are as accurate as needed. To collect this data, I walked through the field at about -36, -27, -18, -9, 0, 9, 18, 27 and 36 inches away from the Polhemus source in the Y direction. Stopping after each step, I stood as still as possible and pressed the center mouse button. My horizontal position may be slightly inaccurate. The data for the X and Y position and direction cosines are acceptable because the correction factor only modifies the Z values and only uses the X and Y for determining the position of the Z. However,

since the value of Z should have always been 68 inches, (the distance from the floor to the sensor on the top of the helmet minus the distance back down to my eyes) there is indeed an error in the Z position and direction. This is shown in the tables in Appendix C. Because the Z position determines the height of the user, without correction the user would appear to walk uphill as he moved away from the sensor.

The correction table was developed using the values collected from walking through the field. Then, using this information and the known height of 68.0 inches, a correction for any point was calculated. Figure 12 shows the rectangular box used

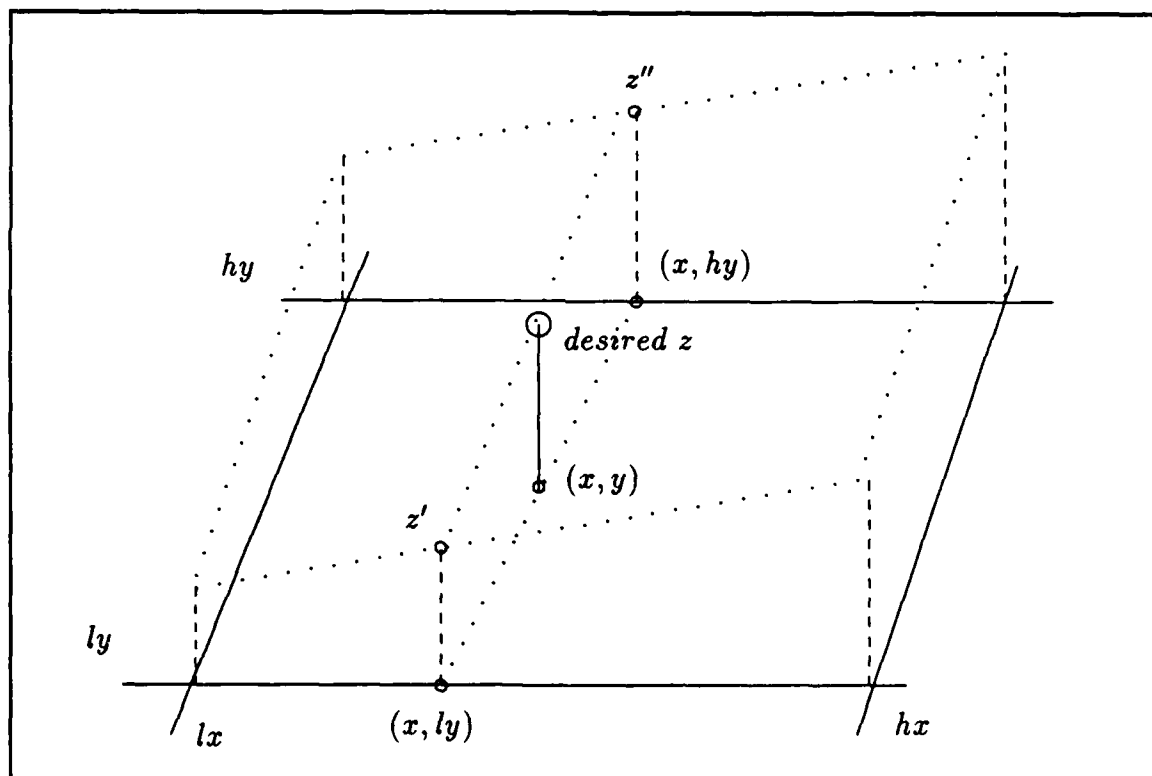


Figure 12. Polhemus Field Vertical Correction

to calculate the correction value. This correction value is the difference between the measured value of  $z$  and the actual value of  $z$ . Using two of these correction values at points,  $(lx, ly)$  and  $(hx, ly)$  in a simple table lookup, a linear interpolation is used

to arrive at the  $z'$  value at point  $(x, ly)$ . Next, the process is repeated for the high Y points, that is,  $(lx, hy)$  and  $(hx, hy)$ . These values are used to interpolate to find the  $z$  correction value for the desired point. This value is then used to modify the value read from the Polhemus to give a more accurate approximation of the  $z$  position. Further testing showed the system worked well until the wearer moved more than three feet in any direction away from the source.

*3.2.5 Predictive Tracking Using the Kalman Filter* The Kalman Filter, as explained in Chapter 2, is used to predict the next position of the head. The image can then be drawn before the user is looking in that direction. The image is then displayed to the user when his head is looking toward the image and not a short lag time later.

A simple Kalman Filter is used as described by equations 3 and 4 (15). The velocity is the derivative of  $x$  with respect to time. The acceleration is the derivative of the velocity with respect to time. To simplify the equations, the acceleration was assumed to be a zero-mean white Gaussian noise process (14:39). This distribution and mean suggest that the user is just as likely to move one direction as another.

$$\frac{dx}{dt} = V \quad (3)$$

$$\frac{dv}{dt} = \text{white noise} \quad (4)$$

The actual function to be modeled is quite simple and is shown in the following equation (14:39).

$$\dot{x} = Fx + Bu + Gw \quad (5)$$

Where  $B = 0$  because the motion is arbitrary and there is no built-in drift to the input data.

The actual Kalman filter equation implemented is shown in equations 6 and 7. The  $F$  matrix is simply the identity matrix in the upper right corner. This may be an over simplification of the problem. However, I decided to start with a simple equation and develop it later if necessary. Further development proved not to be necessary.

$$\begin{bmatrix} \dot{P} \\ \dot{V} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} \begin{bmatrix} P \\ V \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} w \quad (6)$$

These equations can now be used to develop the basic concepts of the algorithm. Assuming that a Kalman filter embodies a constant gain  $K$ , the following equation can be developed (14:137).

$$z = Hx + v = \begin{bmatrix} I & \vdots & 0 \end{bmatrix} \begin{bmatrix} P \\ V \end{bmatrix} + v \quad (7)$$

The next step in the process is to develop the equations for the filter that can be programmed into a computer.

The estimate is updated by defining the Kalman filter gain  $K(t_i)$  and using it in both the mean and covariance relations (13:217).

$$K(t_i) = P(t_i^-)H^T(t_i)[H(t_i)P(t_i^-)H^T(t_i) + R(t_i)]^{-1} \quad (8)$$

$$\hat{x}(t_i^+) = \hat{x}(t_i^-) + K(t_i)[z_i - H(t_i)\hat{x}(t_i^-)] \quad (9)$$

$$P(t_i^+) = P(t_i^-) - K(t_i)H(t_i)P(t_i^-) \quad (10)$$

The following equations are the propagation equations for the Kalman filter from time  $t_{i-1}$  to  $t_i$ .

$$\hat{x}(t_i^-) = \Phi(t_i, t_{i-1})\hat{x}(t_{i-1}^+) \quad (11)$$

$$P(t_i^-) = \Phi(t_i, t_{i-1})P(t_{i-1}^+)\Phi^T(t_i, t_{i-1}) + \int_{t_{i-1}}^{t_i} \Phi(t_i, \tau)G(\tau)Q(\tau)G^T(\tau)\Phi^T(t_i, \tau)d\tau \quad (12)$$

The Kalman filter is developed into the actual equations that are used in the position prediction algorithm. The  $\Phi$  matrix is calculated by the following equations. The  $\Phi$  matrix is the state transition matrix and is the inverse Laplace transform of the inverse of the matrix  $S \times I - F$ . In equation form it is:

$$\Phi = \mathcal{L}^{-1}\{[SI - F]^{-1}\} \quad (13)$$

As stated earlier, the  $F$  matrix is a sparse six by six matrix with the identity matrix in the upper right corner. Given the  $F$  matrix as shown below, the  $SI - F$  matrix is as follows:

$$F = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \text{ and } SI - F = \begin{bmatrix} S & 0 & 0 & -1 & 0 & 0 \\ 0 & S & 0 & 0 & -1 & 0 \\ 0 & 0 & S & 0 & 0 & -1 \\ 0 & 0 & 0 & S & 0 & 0 \\ 0 & 0 & 0 & 0 & S & 0 \\ 0 & 0 & 0 & 0 & 0 & S \end{bmatrix} \quad (14)$$

Given this matrix, the inverse is a fairly simple matrix.

$$[SI - F]^{-1} = \begin{bmatrix} \frac{1}{S} & 0 & 0 & \frac{1}{S^2} & 0 & 0 \\ 0 & \frac{1}{S} & 0 & 0 & \frac{1}{S^2} & 0 \\ 0 & 0 & \frac{1}{S} & 0 & 0 & \frac{1}{S^2} \\ 0 & 0 & 0 & \frac{1}{S} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{S} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{S} \end{bmatrix} \quad (15)$$



The  $\Phi$  matrix is now simply the inverse Laplace transform on each element in the previous matrix. This yields the following  $\Phi$  matrix.

$$\Phi(t) = \begin{bmatrix} 1 & 0 & 0 & t & 0 & 0 \\ 0 & 1 & 0 & 0 & t & 0 \\ 0 & 0 & 1 & 0 & 0 & t \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (16)$$

The  $t$  values in the  $\Phi$  matrix can now be replaced by the time interval of  $t_1 - t_0$ . The  $t_0$  is now replaced with the integration variable  $\tau$ . The final  $\Phi$  matrix that is used in the second part of the  $P$  matrix calculation is shown below.

$$\Phi(t_1, \tau) = \begin{bmatrix} 1 & 0 & 0 & t_1 - \tau & 0 & 0 \\ 0 & 1 & 0 & 0 & t_1 - \tau & 0 \\ 0 & 0 & 1 & 0 & 0 & t_1 - \tau \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (17)$$

This state transition matrix  $\Phi$  is now used in the equations to calculate the  $P$  matrix and the  $\hat{x}(t_i^-)$  propagated values. The  $\Phi$  matrix is also used indirectly in the update equations. Because the  $G$  and  $Q$  matrices are so simple, the second part of equation 12 can be simplified so that integration in real-time is not required. The necessary matrices that are used in the Kalman filter are shown below.

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \quad (18)$$

$$G = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (19)$$

Given the values of 37, 37 and 35 degrees per second per second acceleration values for head movement, provided by AAMRL, the following matrix is used as the  $Q$  matrix.

$$Q = \begin{bmatrix} .37 & 0 & 0 \\ 0 & .37 & 0 \\ 0 & 0 & .35 \end{bmatrix} \quad (20)$$

Assuming that the values from the Polhemus are quite accurate, the allowable error in the  $R$  matrix is set to .01.

$$R = \begin{bmatrix} .01 & 0 & 0 \\ 0 & .01 & 0 \\ 0 & 0 & .01 \end{bmatrix} \quad (21)$$

Another assumption that was made is that since the BSP tree code will draw about the same number of polygons each time, the amount of time between frames is approximately constant. This allowed another simplification of the filter equations that were used in the system. The  $t$  in the  $\Phi$  matrix then becomes 0.1, or one tenth of a second, which is the approximate cycle time of the system.

The equations are coded into a routine, *predict.c*, that consists of the *update* and *propagate* subroutines as well as utilities and initialization routines. These routines are called by the *display* program during each draw cycle, if the Kalman filter option has been selected. If selected the propagate routine is called every cycle, while

the update is only called when new Polhemus data is available. This allows the filter to propagate the estimate of the position until a Polhemus value is received. When a Polhemus value is available, the filter first calculates an update, then the propagate.

For the system to function properly the  $P$  and the  $x$  matrices had to be initialized. The  $x$  matrix is initialized to zero and the  $P$  matrix is initialized as shown below.

$$P = \begin{bmatrix} .1 & 0 & 0 & 0 & 0 & 0 \\ 0 & .1 & 0 & 0 & 0 & 0 \\ 0 & 0 & .1 & 0 & 0 & 0 \\ 0 & 0 & 0 & .1 & 0 & 0 \\ 0 & 0 & 0 & 0 & .1 & 0 \\ 0 & 0 & 0 & 0 & 0 & .1 \end{bmatrix} \quad (22)$$

### 3.3 Summary

This chapter has described the hardware and software that was developed for the AFIT HMD system.

The completed system is shown, with front cover removed in Figure 13. The mounting system is made as flexible as possible. This allows the system to be mounted on several different types of helmets or head gear. The color displays are the highest resolution color LCD displays that are presently commercially available. The computer graphics image on the Silicon Graphics Iris 3130 workstation is converted to a NTSC composite video signal by using a convertor/encoder. The optics decided upon are simple, inexpensive, and effective, but not the best available. Finally the position and orientation of the user is reported to the workstation by a Polhemus 3-Space tracking system.

The basis of the software is a set of previously written programs that manipulate a BSP tree of polygons to display an image. The displayed image is properly shaded and rendered so that hidden surfaces are not visible. A simple Kalman fil-

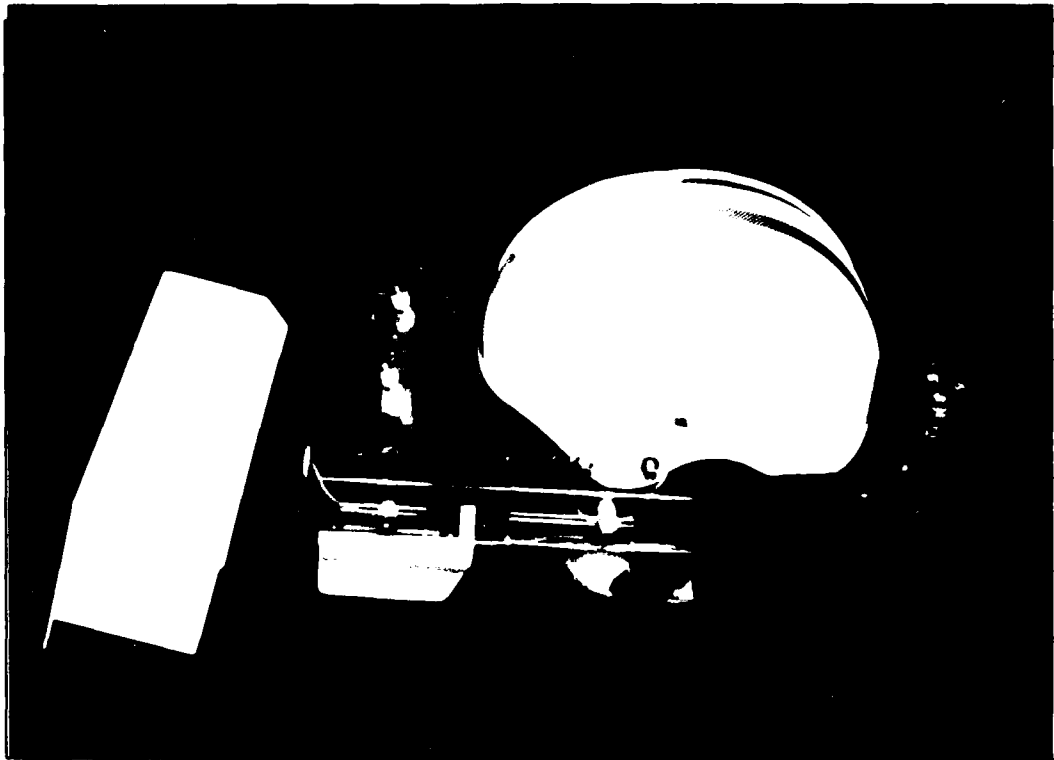


Figure 13. AFIT HMD system, with front cover removed

ter was added to attempt to predict the orientation of the helmet at the next time interval.

The following chapter reports the findings of the development, including improvements in the design. It also reports the results of the testing and evaluation of the entire system; hardware and software.

## *IV. Results/Findings*

The AFIT HMD system was very successful. The testing and evaluation of the developed system showed some minor deficiencies that may be the basis for future research. These are described in this chapter. This chapter also describes the results of each portion of the project and shows some sample output.

### *4.1 HMD construction*

The basic hardware for the system was completed in September 1988. Testing began almost before the system was operational. The hardware for the most part is very robust. Two minor problems were encountered in the system during the testing.

First, the power connection turned out to be a problem because it occasionally would become disconnected and interrupt a test or demonstration of the system. The fix for the problem was to find a connector that did not simply plug into a socket. However, to find such a receptacle that is small and light-weight was not a trivial task. I settled on a Jones connector that plugs downward into a socket mounted on the rear of the plastic ring.

Second, the front cover of the system serves two purposes. First, it offers a degree of protection to the system. The second purpose is to reduce, if not totally eliminate, outside light reflections. The original top and bottom covers were made of one eighth inch plastic and proved to be too heavy. The cover was then redesigned out of lightweight vacuum-formed plastic.

### *4.2 RGB to NTSC Encoder/Convertor*

The inexpensive convertor used to change the output RGB signal to a composite video signal did not reproduce the colors that the workstation displayed. The displayed image appeared slightly green tinted.

The Lyon Lamb equipment arrived in late October 1988 and proved to be much more satisfactory. This new equipment did reproduce the exact colors generated by the Silicon Graphics workstation. The resulting image in the HMD was clear, sharp and showed vibrant, bright colors. The results of using this equipment were far better than the inexpensive convertor.

#### *4.3 Display Program*

The software was completed in stages. The first working software had no features other than basically displaying the image to the user. A sample image of the room database is shown in Figure 14.

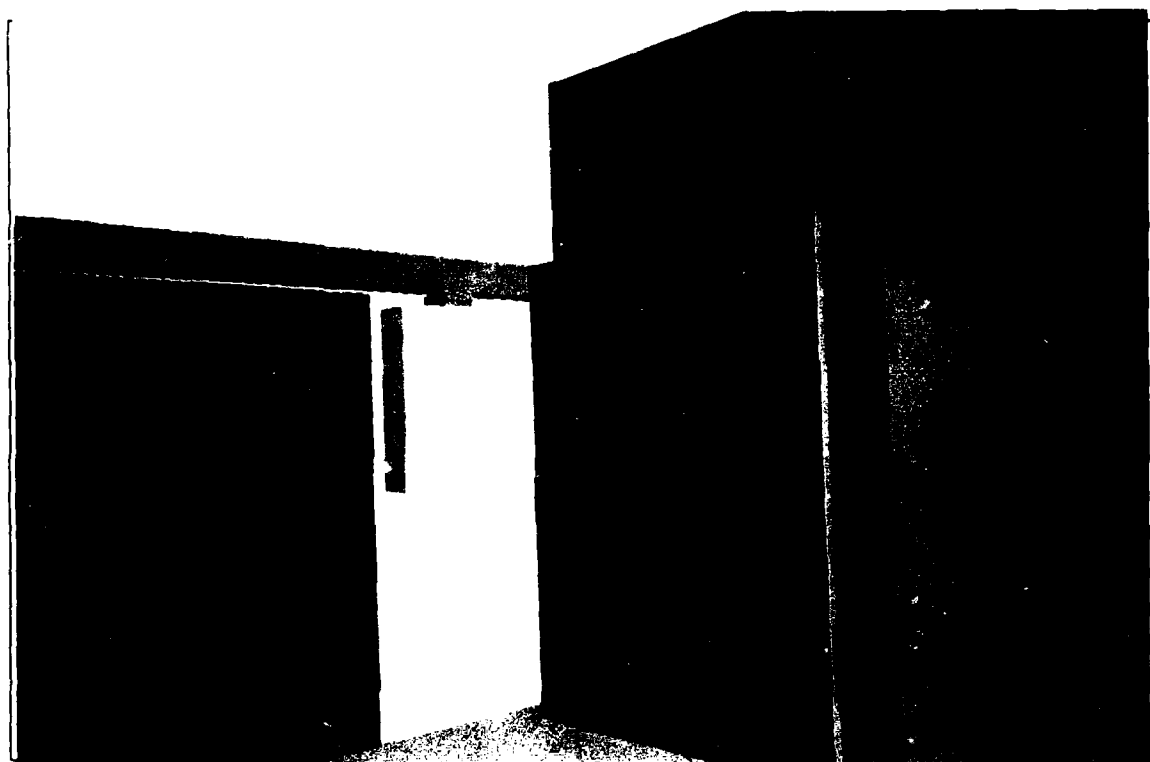


Figure 14. Room Database as Displayed on the HMD System

The next development involved the use of the mouse for "flying" through a data base. If the user presses the left mouse button, he will move backward along his her present line of sight. If the user presses the right or middle mouse button, he will move forward at full or half speed, respectively.

#### *4.4 Polhemus Field Correction*

The correction of the Polhemus field was the next task accomplished. The system does have some restrictions because the Polhemus field is only corrected to three feet in any direction. If the user of the HMD system walks outside this limitation, the position and direction information reported to the computer becomes unreliable and the displayed image becomes unusable.

#### *4.5 Predictive Tracking using a Kalman Filter*

A Kalman filter routine was added to predict the next direction the user would be looking.

The average user is more likely to turn his head quickly than to change his position quickly by running across the room. The Kalman filter simply attempts to predict where the wearer of the helmet will be looking when the processor has had enough time to draw an image. The image that the processor draws for the wearer to view is based on a prediction of where the user will be looking at the next instant in time.

The prediction of next position is very accurate when the movement of the head is slow. The Kalman filter appears to improve to the system whenever the image update time is longer than about one quarter of a second, by building an image for display before the user is looking in that direction. This occurs whenever the image complexity is greater than 1000 displayed polygons. However, the Kalman filter routine does not produce any visible improvement when used with smaller databases.

The most visible effect of the Kalman filter routine was the oscillating of the displayed image when user head movements came to an abrupt halt. The results were not as good as expected. This could have been due to the oversimplification of the filter routine or simply that the movement of the human head does not fit well into a linear model.

#### *4.6 Tracker initialization*

Further research showed that the 3-Space tracker could have been initialized to provide the exact coordinates needed in this effort (16:5-2). The modifications to the data read, ie, the adjustment for the height measured from the floor, would not have been necessary. If the initialization code were modified to reflect this change, the calculations for positional information in the *getpos* routine would be slightly easier to understand.

#### *4.7 Images Displayed*

The system worked better than expected. The conversion programs that were developed allowed the system to display any AFIT/AFWL polygon format file. Objects as diverse as a threat database by Captain Mark Kanko, a terrain database by Lieutenant LeAnne Roberts, a DC-10 model by Captain Gary Lorimor, and a floating sphere were viewed.

A view of a target runway surrounded by threat envelopes is shown in Figure 15. This image was captured by wearing the helmet and "flying" through the previously generated threat database. Other images that were viewed are shown in Figures 16 through 18.

#### *4.8 Summary*

The completed system was very successful. The image display update rate or the time between images was extremely fast. It appears that with a small database



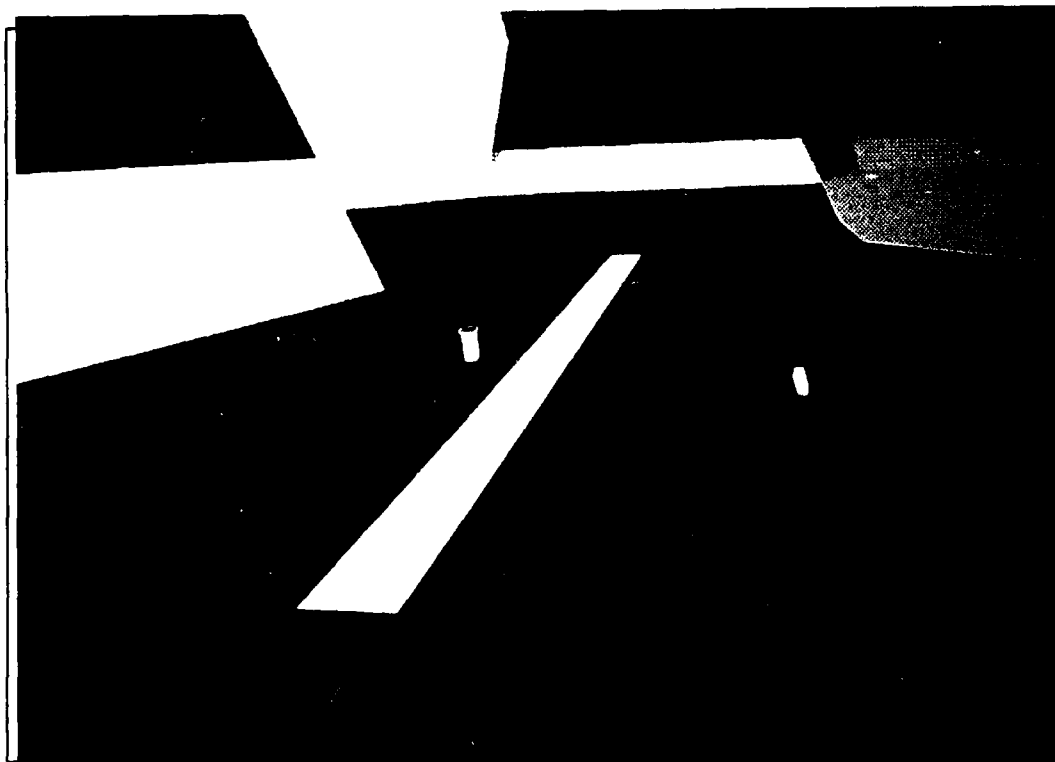


Figure 15. An Airport Target in Mark Kanko's Threat Database

of under 500 polygons, the update rate was a function of the speed the workstation could draw the image and not a function of how fast the BSP tree algorithm traversed the tree. This observation leads to a conclusion that faster display hardware will indeed allow simple images to be displayed in full color and shaded in real time.

The only delay that is noticeable in the system is the lag time that is observed when the helmet is moved quickly. The displayed image takes about one third of a second to "catch up" to the position information. Testing the system indicates that this lag is due to the slow response from the Polhemus tracking device. When a poll is sent to the Polhemus, the data must be routed through the UNIX operating system. The response from the Polhemus is only available to the display program after UNIX has serviced the interrupt. A significant increase in speed would be noticed if the program were to bypass the UNIX environment, if possible, and communicate directly with the Polhemus.

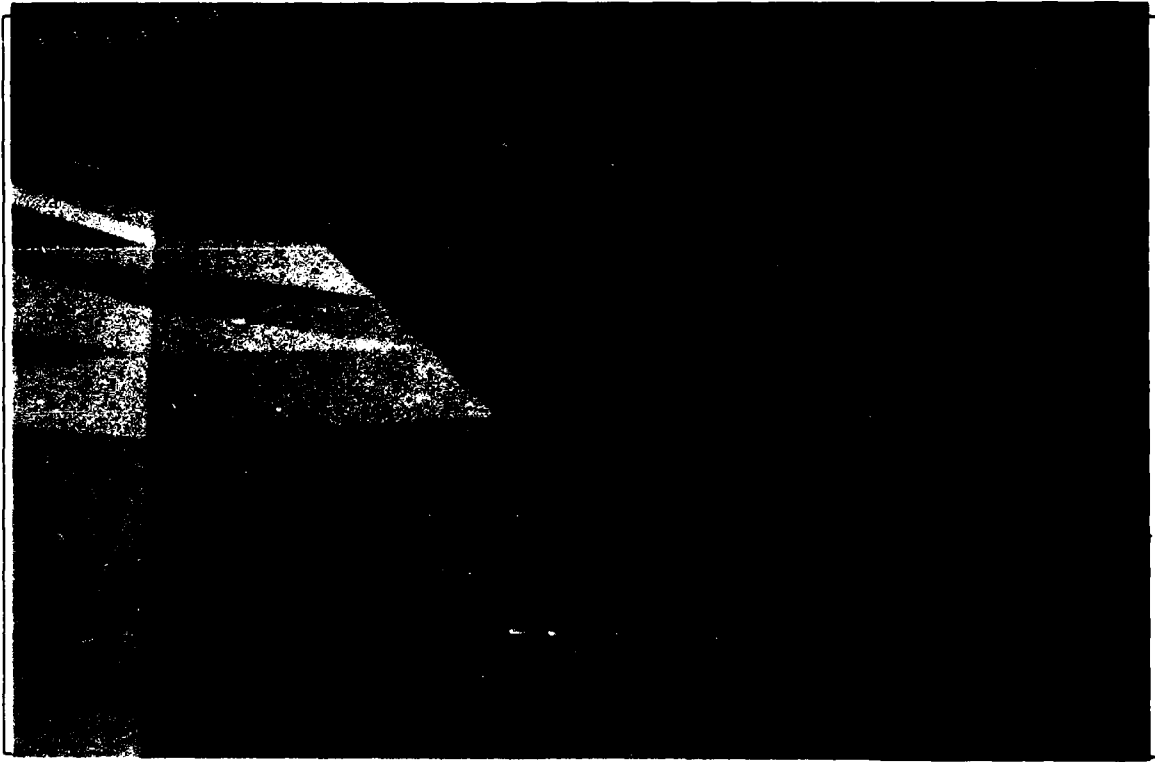


Figure 16. Flying Over a Digitized Terrain Map

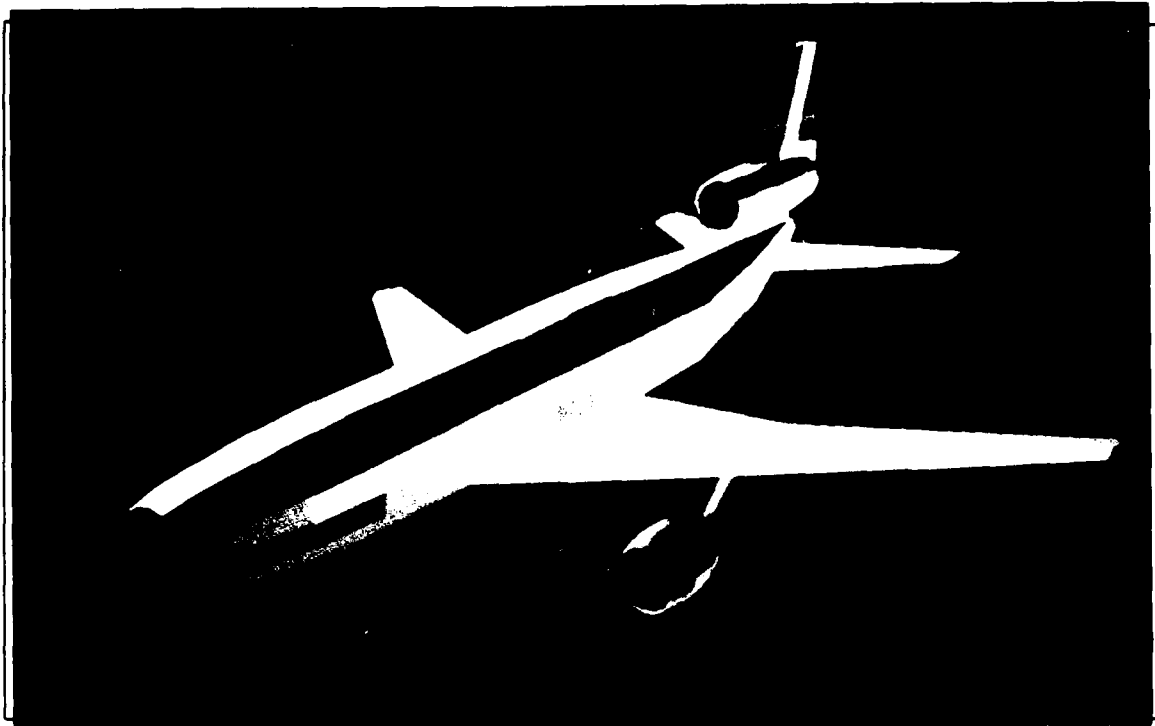


Figure 17. Examining a model of a DC-10

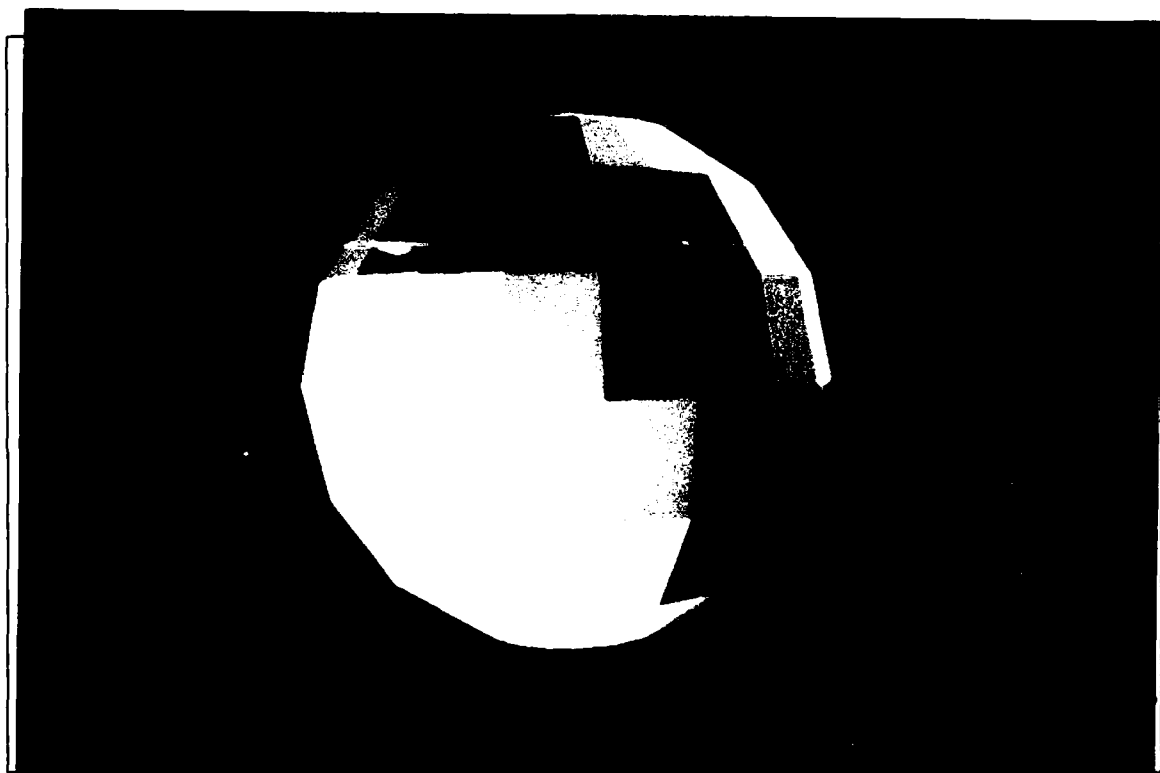


Figure 18. A Three-Dimensional Floating Sphere

## *V. Conclusions/Recommendations*

As mentioned in the beginning of this effort, the goal of the AFIT HMD System was to build a simple, inexpensive, color helmet-mounted display system that places the user in a visual virtual world. The AFIT Helmet-Mounted Virtual Environment Display System does that and has proven to be a great success.

As mentioned in the previous chapter, even with all the calculations involved in calculating the position of the user and traversing the BSP tree, the system must still wait for the much slower response from the poll sent to the Polhemus tracking system. This is evidence that the system could indeed be faster if a more efficient and accurate position and direction tracking system were to become available.

There are, however, ways to improve or modify any system. The AFIT HMD system is no exception.

### *5.1 Possible Improvements*

The HMD system is an initial prototype. Many improvements may be made to the hardware and some to the software to produce a better system. The HMD system could be improved by using higher resolution color displays when they become available. The weight of the system could be reduced by using lighter weight plastic and mounting the LCD driver electronics off the head or using LCD displays that accept a direct video or RGB signal. More flexible and lighter weight cable could also be used in the system to reduce weight.

The optical system is not optimal either. The optics are small and very simple. A better optical solution could be developed. In fact, if the LCD displays were changed, the optics would probably need to be changed to match the new displays. If a new display were used that is less than 69 mm across, there would be no need for the press-on prisms.

The use of the Kalman filter to predict the future position of the helmet was not very conclusive. Further investigation into the Kalman filter is definitely justified. Because the filter routines can and usually do run independently of any other routine, future improvements should run the Kalman filter program on a separate processor. The separate processor could poll the Polhemus and run the Kalman filter in a continuous cycle. When the display program on the graphics workstation requires a position value, the separate processor would send the current position information. This position and direction information would be either directly from the Polhemus, passed through one update cycle, or a propagated value from a previous Polhemus value. Either way, the display processor would be given the needed position information when it is needed. This type of configuration would greatly reduce the lag time caused by the retrieving of the positional information.

Because the LCD displays are wider than the distance between a users pupils, prisms were required to diffract the users line of sight. The user looks straight ahead and sees the displays that are mounted outward of his line of sight. An alternate solution to this problem, as shown in Figure 19, would be to display slightly different images on each display. The user could then look straight ahead at the display and see the same image on each screen only not in the same place on each screen, thus eliminating the need for the prisms. Notice that the same image is on each screen, only in slightly different places. This allows the user to look straight ahead and not see different images with each eye. The pupil distance could be an input to the program, thus eliminating one of the necessary adjustments to the system. This would also provide a smaller amount of overlap and thus increase the horizontal field of view. Such a modification would also allow for stereoscopic images if so desired. Although for the present application, stereo is not required.

Many improvements could be made to the system but just as interesting are the possible applications. The AFIT HMD system should be used to visualize information and data that is three-dimensional in nature. Whenever a project is concerned

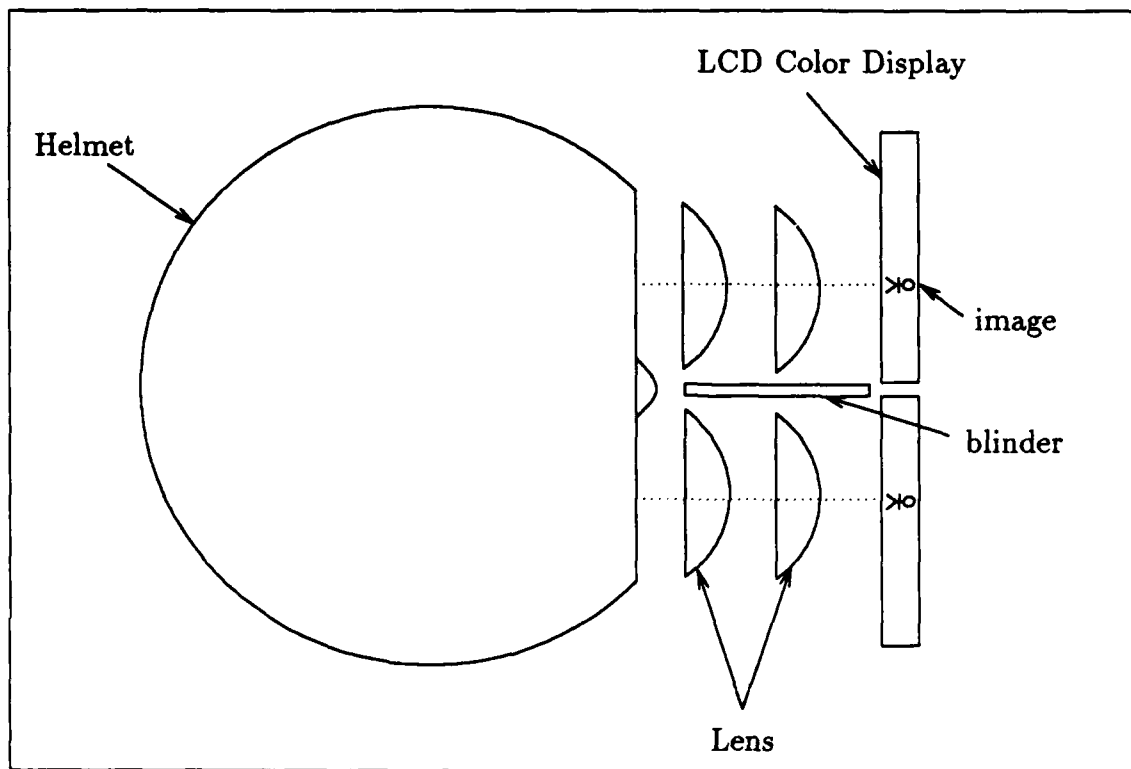


Figure 19. Proposed New HMD Design

with information that cannot be easily visualized by a paper drawing or on a CRT, a HMD system should be considered.

The AFIT HMD system has the potential to become a very useful tool in training and research.

## 5.2 Future Applications

Currently, Captain Gary Lorimor is using the AFIT HMD system to display time dependent data (12:3). He has taken actual data from several engagements over the Red Flag range in Nevada and has developed the software to display the battle scene on the HMD system. The HMD user is placed out in the range and he can move about, enter and exit cockpits and see what the original pilot saw, all by the use of the mouse buttons. Such a system has many uses in training, preparing

for and in review of a mission. The objects in this system are color coded red and blue for enemy and friendly aircraft. Proper identification of these aircraft would be almost impossible without the use of color displays.

A color helmet-mounted display system could be used to visualize volumetric data. An engineer could walk through an aerodynamic flow field to get a real feel for the shape and complexity of the flow.

With only a little modification to the software, the HMD system could be displaying video images instead of computer generated images. A remote video camera could be connected to the HMD system by cable or radio. If the camera were mounted on servo motors, the camera could be moved as the helmet moves. This would allow the system to be used in Remote Robotic applications.

Because the HMD system can display a full color shaded image to the user, it could be used in a flight simulator. The processor need only calculate the image where the pilot is looking. The processor would then have more time to run the simulation. The pilot would see full color images of the cockpit and the outside world. Also, a single simulator could become any type of aircraft with only a change of the database. This is a step toward the Super Cockpit envisioned by AAMRL as mentioned in Chapter 1.

Another possible application would be in high threat areas. Other countries are experimenting with the use of lasers to blind pilots. A HMD system could easily be configured to block out all external light sources. The sources of the image the pilot would see could be either computer generated, using radar data, or a video image from a camera pickup mounted on the helmet.

Lastly, experimentation should be done using the HMD system to reduce motion sickness and possibly provide high G tolerant flying. If future tests show that a pilot could lie down in the cockpit, without experiencing motion sickness or disorientation, then the pilot could withstand much higher forces than currently possible.

The pilot could then see forward by the use of a helmet-mounted display system.

The AFIT HMD system has been a great success and future research will show that similar systems will someday be as commonplace as the graphics terminal of today. A user can wear an HMD system and explore horizons not possible with the current limited two-dimensional displays.



## Appendix A. *User's Manual*

The AFIT HMD system was designed with simplicity in mind.

In order to use the *display* program, the database must be in a binary BSP tree format. The programs *treemaker* and *new2old* accomplish that task.

The script file *new2bsp* calls both *treemaker* and *new2old* to generate a binary BSP tree file. The script file is used by running the program with a command line parameter of an AFIT format polygon file (*filename.new*). The polygon file may have comments on any line that begins with a '%'. The script, *new2bsp*, strips out the comments, makes an old UNC format polygon file, makes a binary BSP tree file, then lastly, deletes all temporary files.

However, the manual method is still available, if desired. That being to run the *new2old* against a valid AFIT format polygon file. This would then create an UNC format polygon file. Then *treemaker* could be run to generate a BSP tree file.

*Treemaker* accepts an input file of polygons and creates a BSP tree. After the tree is created, it is possible to save the results to a file. Two formats are available: binary and ASCII. To use *display* for viewing, a binary BSP tree is needed. *Treemaker -h* will provide some additional flag information.

*Display* can be used to view a BSP tree, and the mouse is used to move forward, backward and reset the scale and position. To move backward the user must press the left mouse button. The center and right mouse button will move the user forward at half and full speed, respectively. The user may also reset the scale to 1.0 and be placed at (0,0,0) by pressing the outer two mouse buttons simultaneously.

The directional information is taken from a sensor on the top of the helmet. Wherever the wearer looks, he will see the image in that direction and will travel in that direction by the use of the mouse.

A help menu is available. It lists all the available options in *display*, and is the first screen displayed. *Display* will run on the SG in either NTSC or 60Hz mode. The system is designed to default to the NTSC mode. To use it in the 60Hz mode, simply use **display -h**. The display program also is designed to run with or without the Kalman filter routine. If the Kalman filter routine is desired, simply add a **-k** to the display command line.

*Display* prompts the user for a BSP file and then reads the binary BSP tree from that file and reads viewing parameters from standard input.

A standard UNIX *makefile* is also provided for compiling and linking the software system. The system is designed to run on the SG 3130 and minor software modifications would be necessary in *initpol.c*, *bsp.c* and *graphics.c* to port the system to another workstation.

## Appendix B. *Room Data Base*

The following is the listing of the data base created for the room in which the Polhemus source is mounted.

Polygon file of section of room 241

ccw

points 236 patches 59

% describe the floor of the room

|        |         |      |       |      |      |      |        |      |      |      |
|--------|---------|------|-------|------|------|------|--------|------|------|------|
| -80.00 | 64.00   | 0.00 | color | 0.60 | 0.55 | 0.55 | normal | 0.00 | 0.00 | 1.00 |
| -80.00 | -104.00 | 0.00 | color | 0.60 | 0.55 | 0.55 | normal | 0.00 | 0.00 | 1.00 |
| 103.00 | -104.00 | 0.00 | color | 0.60 | 0.55 | 0.55 | normal | 0.00 | 0.00 | 1.00 |
| 103.00 | 64.00   | 0.00 | color | 0.60 | 0.55 | 0.55 | normal | 0.00 | 0.00 | 1.00 |

% describe the ceiling

|        |         |        |       |      |      |      |        |      |      |       |
|--------|---------|--------|-------|------|------|------|--------|------|------|-------|
| -80.00 | 64.00   | 115.00 | color | 0.85 | 0.85 | 0.85 | normal | 0.00 | 0.00 | -1.00 |
| -80.00 | -104.00 | 115.00 | color | 0.85 | 0.85 | 0.85 | normal | 0.00 | 0.00 | -1.00 |
| 80.00  | -104.00 | 115.00 | color | 0.85 | 0.85 | 0.85 | normal | 0.00 | 0.00 | -1.00 |
| 80.00  | 64.00   | 115.00 | color | 0.85 | 0.85 | 0.85 | normal | 0.00 | 0.00 | -1.00 |

% describe the wall behind the conduit

|        |       |        |       |      |      |      |        |       |      |      |
|--------|-------|--------|-------|------|------|------|--------|-------|------|------|
| -80.00 | 64.00 | 0.00   | color | 0.95 | 0.95 | 0.95 | normal | -1.00 | 0.00 | 0.00 |
| -80.00 | 64.00 | 115.00 | color | 0.95 | 0.95 | 0.95 | normal | -1.00 | 0.00 | 0.00 |
| 80.00  | 64.00 | 115.00 | color | 0.95 | 0.95 | 0.95 | normal | -1.00 | 0.00 | 0.00 |
| 80.00  | 64.00 | 0.00   | color | 0.95 | 0.95 | 0.95 | normal | -1.00 | 0.00 | 0.00 |

% describe the wall behind the bookcases

|        |        |        |       |      |      |      |        |      |       |      |
|--------|--------|--------|-------|------|------|------|--------|------|-------|------|
| -80.00 | 64.00  | 0.00   | color | 0.90 | 0.90 | 0.90 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | 64.00  | 115.00 | color | 0.90 | 0.90 | 0.90 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -42.00 | 115.00 | color | 0.90 | 0.90 | 0.90 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -42.00 | 0.00   | color | 0.90 | 0.90 | 0.90 | normal | 0.00 | -1.00 | 0.00 |

% describe a door

|        |        |       |       |      |      |      |        |      |       |      |
|--------|--------|-------|-------|------|------|------|--------|------|-------|------|
| -80.00 | -42.00 | 0.00  | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -42.00 | 85.00 | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -72.50 | 85.00 | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -72.50 | 0.00  | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |

% describe another door

|        |        |      |       |      |      |      |        |      |       |      |
|--------|--------|------|-------|------|------|------|--------|------|-------|------|
| -80.00 | -73.50 | 0.00 | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |
|--------|--------|------|-------|------|------|------|--------|------|-------|------|

|        |         |       |       |      |      |      |        |      |       |      |
|--------|---------|-------|-------|------|------|------|--------|------|-------|------|
| -80.00 | -73.50  | 85.00 | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -104.00 | 85.00 | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -104.00 | 0.00  | color | 0.56 | 0.29 | 0.10 | normal | 0.00 | -1.00 | 0.00 |

% describe the wood wall above the doors

|        |         |        |       |      |      |      |        |      |       |      |
|--------|---------|--------|-------|------|------|------|--------|------|-------|------|
| -80.00 | -42.00  | 85.00  | color | 0.76 | 0.29 | 0.00 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -42.00  | 115.00 | color | 0.76 | 0.29 | 0.00 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -104.00 | 115.00 | color | 0.76 | 0.29 | 0.00 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | -104.00 | 85.00  | color | 0.76 | 0.29 | 0.00 | normal | 0.00 | -1.00 | 0.00 |

% describe the small bookcase

|        |        |       |       |      |      |      |        |       |       |      |
|--------|--------|-------|-------|------|------|------|--------|-------|-------|------|
| -80.00 | -41.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -66.00 | -41.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -66.00 | -41.00 | 52.00 | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -80.00 | -41.00 | 52.00 | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -80.00 | -41.00 | 52.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -66.00 | -41.00 | 52.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -66.00 | -8.00  | 52.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -80.00 | -8.00  | 52.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -66.00 | -41.00 | 52.00 | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -66.00 | -8.00  | 52.00 | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -66.00 | -8.00  | 0.00  | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -66.00 | -41.00 | 0.00  | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -80.00 | -8.00  | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |
| -66.00 | -8.00  | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |
| -66.00 | -8.00  | 52.00 | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |
| -80.00 | -8.00  | 52.00 | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |

% describe the medium bookcase

|        |       |       |       |      |      |      |        |       |      |      |
|--------|-------|-------|-------|------|------|------|--------|-------|------|------|
| -80.00 | -7.00 | 80.00 | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00 | 0.00 |
| -80.00 | -7.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00 | 0.00 |
| -66.00 | -7.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00 | 0.00 |
| -66.00 | -7.00 | 80.00 | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00 | 0.00 |
| -80.00 | -7.00 | 80.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00 | 1.00 |
| -66.00 | -7.00 | 80.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00 | 1.00 |
| -66.00 | 26.00 | 80.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00 | 1.00 |
| -80.00 | 26.00 | 80.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00 | 1.00 |

|        |       |       |       |      |      |      |        |      |       |      |
|--------|-------|-------|-------|------|------|------|--------|------|-------|------|
| -66.00 | -7.00 | 80.00 | color | 0.40 | 0.26 | 0.00 | normal | 0.00 | -1.00 | 0.00 |
| -66.00 | -7.00 | 0.00  | color | 0.40 | 0.26 | 0.00 | normal | 0.00 | -1.00 | 0.00 |
| -66.00 | 26.00 | 0.00  | color | 0.40 | 0.26 | 0.00 | normal | 0.00 | -1.00 | 0.00 |
| -66.00 | 26.00 | 80.00 | color | 0.40 | 0.26 | 0.00 | normal | 0.00 | -1.00 | 0.00 |
| -80.00 | 26.00 | 80.00 | color | 0.37 | 0.20 | 0.00 | normal | 1.00 | 0.00  | 0.00 |
| -80.00 | 26.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | 1.00 | 0.00  | 0.00 |
| -66.00 | 26.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | 1.00 | 0.00  | 0.00 |
| -66.00 | 26.00 | 80.00 | color | 0.37 | 0.20 | 0.00 | normal | 1.00 | 0.00  | 0.00 |

% describe the large bookcase

|        |       |       |       |      |      |      |        |       |       |      |
|--------|-------|-------|-------|------|------|------|--------|-------|-------|------|
| -80.00 | 27.00 | 96.00 | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -80.00 | 27.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -66.00 | 27.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -66.00 | 27.00 | 96.00 | color | 0.37 | 0.20 | 0.00 | normal | -1.00 | 0.00  | 0.00 |
| -66.00 | 27.00 | 96.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -80.00 | 27.00 | 96.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -80.00 | 58.00 | 96.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -66.00 | 58.00 | 96.00 | color | 0.37 | 0.30 | 0.00 | normal | 0.00  | 0.00  | 1.00 |
| -66.00 | 27.00 | 96.00 | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -66.00 | 27.00 | 0.00  | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -66.00 | 58.00 | 0.00  | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -66.00 | 58.00 | 96.00 | color | 0.40 | 0.26 | 0.00 | normal | 0.00  | -1.00 | 0.00 |
| -66.00 | 58.00 | 96.00 | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |
| -66.00 | 58.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |
| -80.00 | 58.00 | 0.00  | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |
| -80.00 | 58.00 | 96.00 | color | 0.37 | 0.20 | 0.00 | normal | 1.00  | 0.00  | 0.00 |

% describe the first power box

|        |       |       |       |      |      |      |        |       |      |      |
|--------|-------|-------|-------|------|------|------|--------|-------|------|------|
| -53.00 | 57.00 | 40.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |
| -53.00 | 57.00 | 70.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |
| -29.00 | 57.00 | 70.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |
| -29.00 | 57.00 | 40.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |
| -53.00 | 57.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00  | 1.00 | 0.00 |
| -53.00 | 64.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00  | 1.00 | 0.00 |
| -53.00 | 64.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00  | 1.00 | 0.00 |
| -53.00 | 57.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00  | 1.00 | 0.00 |

|        |       |       |       |      |      |      |        |      |      |       |
|--------|-------|-------|-------|------|------|------|--------|------|------|-------|
| -53.00 | 57.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |
| -53.00 | 64.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |
| -29.00 | 64.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |
| -29.00 | 57.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |

|        |       |       |       |      |      |      |        |      |       |      |
|--------|-------|-------|-------|------|------|------|--------|------|-------|------|
| -29.00 | 57.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |
| -29.00 | 64.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |
| -29.00 | 64.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |
| -29.00 | 57.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |

|        |       |       |       |      |      |      |        |      |      |      |
|--------|-------|-------|-------|------|------|------|--------|------|------|------|
| -53.00 | 57.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |
| -53.00 | 64.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |
| -29.00 | 64.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |
| -29.00 | 57.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |

% describe the second power box

|       |       |       |       |      |      |      |        |       |      |      |
|-------|-------|-------|-------|------|------|------|--------|-------|------|------|
| 65.00 | 57.00 | 40.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |
| 65.00 | 57.00 | 70.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |
| 41.00 | 57.00 | 70.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |
| 41.00 | 57.00 | 40.00 | color | 0.70 | 0.70 | 0.70 | normal | -1.00 | 0.00 | 0.00 |

|       |       |       |       |      |      |      |        |      |      |      |
|-------|-------|-------|-------|------|------|------|--------|------|------|------|
| 65.00 | 57.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | 1.00 | 0.00 |
| 65.00 | 64.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | 1.00 | 0.00 |
| 65.00 | 64.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | 1.00 | 0.00 |
| 65.00 | 57.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | 1.00 | 0.00 |

|       |       |       |       |      |      |      |        |      |      |       |
|-------|-------|-------|-------|------|------|------|--------|------|------|-------|
| 65.00 | 57.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |
| 65.00 | 64.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |
| 41.00 | 64.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |
| 41.00 | 57.00 | 40.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | -1.00 |

|       |       |       |       |      |      |      |        |      |       |      |
|-------|-------|-------|-------|------|------|------|--------|------|-------|------|
| 41.00 | 57.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |
| 41.00 | 64.00 | 40.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |
| 41.00 | 64.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |
| 41.00 | 57.00 | 70.00 | color | 0.50 | 0.50 | 0.50 | normal | 0.00 | -1.00 | 0.00 |

|       |       |       |       |      |      |      |        |      |      |      |
|-------|-------|-------|-------|------|------|------|--------|------|------|------|
| 65.00 | 57.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |
| 65.00 | 64.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |
| 41.00 | 64.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |
| 41.00 | 57.00 | 70.00 | color | 0.65 | 0.65 | 0.65 | normal | 0.00 | 0.00 | 1.00 |

% describe the conduit

|        |       |        |       |      |      |      |        |       |       |       |
|--------|-------|--------|-------|------|------|------|--------|-------|-------|-------|
| -44.00 | 64.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 1.00  | 0.00  |
| -44.00 | 64.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 1.00  | 0.00  |
| -44.00 | 58.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 1.00  | 0.00  |
| -44.00 | 58.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 1.00  | 0.00  |
| -44.00 | 58.00 | 78.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -44.00 | 58.00 | 72.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| 80.00  | 58.00 | 72.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| 80.00  | 58.00 | 78.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -38.00 | 58.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | -1.00 |
| -38.00 | 64.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | -1.00 |
| 80.00  | 64.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | -1.00 |
| 80.00  | 58.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | -1.00 |
| -44.00 | 64.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | 1.00  |
| -44.00 | 58.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | 1.00  |
| 80.00  | 58.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | 1.00  |
| 80.00  | 64.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 0.00  | 1.00  |
| -44.00 | 58.00 | 72.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -38.00 | 58.00 | 72.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -38.00 | 58.00 | 70.00  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -44.00 | 58.00 | 70.00  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| 50.00  | 58.00 | 72.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| 56.00  | 58.00 | 72.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| 56.00  | 58.00 | 70.00  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| 50.00  | 58.00 | 70.00  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -26.00 | 58.00 | 78.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -20.00 | 58.00 | 78.50  | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -20.00 | 58.00 | 115.00 | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -26.00 | 58.00 | 115.00 | color | 0.50 | 0.50 | 0.50 | normal | -1.00 | 0.00  | 0.00  |
| -38.00 | 64.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | -1.00 | 0.00  |
| -38.00 | 64.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | -1.00 | 0.00  |
| -38.00 | 58.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | -1.00 | 0.00  |
| -38.00 | 58.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | -1.00 | 0.00  |
| 50.00  | 58.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 1.00  | 0.00  |
| 50.00  | 58.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00  | 1.00  | 0.00  |

|        |       |        |       |      |      |      |        |      |       |      |
|--------|-------|--------|-------|------|------|------|--------|------|-------|------|
| 50.00  | 64.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | 1.00  | 0.00 |
| 50.00  | 64.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | 1.00  | 0.00 |
| 56.00  | 58.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |
| 56.00  | 64.00 | 72.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |
| 56.00  | 64.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |
| 56.00  | 58.00 | 70.00  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |
| -26.00 | 58.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | 1.00  | 0.00 |
| -26.00 | 58.00 | 115.00 | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | 1.00  | 0.00 |
| -26.00 | 64.00 | 115.00 | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | 1.00  | 0.00 |
| -26.00 | 64.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | 1.00  | 0.00 |
| -20.00 | 58.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |
| -20.00 | 64.00 | 78.50  | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |
| -20.00 | 64.00 | 115.00 | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |
| -20.00 | 58.00 | 115.00 | color | 0.40 | 0.40 | 0.40 | normal | 0.00 | -1.00 | 0.00 |

% describe the room divider against the wall

|        |       |       |       |      |      |      |        |       |       |      |
|--------|-------|-------|-------|------|------|------|--------|-------|-------|------|
| -22.00 | 62.00 | 0.00  | color | 1.00 | 0.10 | 0.10 | normal | -1.00 | 0.00  | 0.00 |
| 38.00  | 62.00 | 0.00  | color | 1.00 | 0.10 | 0.10 | normal | -1.00 | 0.00  | 0.00 |
| 38.00  | 62.00 | 72.00 | color | 1.00 | 0.10 | 0.10 | normal | -1.00 | 0.00  | 0.00 |
| -22.00 | 62.00 | 72.00 | color | 1.00 | 0.10 | 0.10 | normal | -1.00 | 0.00  | 0.00 |
| -22.00 | 62.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 1.00  | 0.00 |
| -22.00 | 62.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 1.00  | 0.00 |
| -22.00 | 64.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 1.00  | 0.00 |
| -22.00 | 64.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 1.00  | 0.00 |
| -22.00 | 62.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00  | 1.00 |
| 38.00  | 62.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00  | 1.00 |
| 38.00  | 64.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00  | 1.00 |
| -22.00 | 64.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00  | 1.00 |
| 38.00  | 62.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | -1.00 | 0.00 |
| 38.00  | 62.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | -1.00 | 0.00 |
| 38.00  | 64.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | -1.00 | 0.00 |
| 38.00  | 64.00 | 72.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | -1.00 | 0.00 |

% describe the divider wall oposite the power panels

|        |        |       |       |      |      |      |        |      |      |      |
|--------|--------|-------|-------|------|------|------|--------|------|------|------|
| -22.00 | -78.00 | 0.00  | color | 1.00 | 0.10 | 0.10 | normal | 1.00 | 0.00 | 0.00 |
| -22.00 | -78.00 | 65.00 | color | 1.00 | 0.10 | 0.10 | normal | 1.00 | 0.00 | 0.00 |



|        |        |       |       |      |      |      |        |      |      |      |
|--------|--------|-------|-------|------|------|------|--------|------|------|------|
| 134.00 | -78.00 | 65.00 | color | 1.00 | 0.10 | 0.10 | normal | 1.00 | 0.00 | 0.00 |
| 134.00 | -78.00 | 0.00  | color | 1.00 | 0.10 | 0.10 | normal | 1.00 | 0.00 | 0.00 |
| -22.00 | -78.00 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 1.00 | 0.00 |
| -22.00 | -78.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 1.00 | 0.00 |
| -22.00 | -80.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 1.00 | 0.00 |
| -22.00 | -80.00 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 1.00 | 0.00 |
| -22.00 | -78.00 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 0.00 | 1.00 |
| 134.00 | -78.00 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 0.00 | 1.00 |
| 134.00 | -80.00 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 0.00 | 1.00 |
| -22.00 | -80.00 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00 | 0.00 | 1.00 |
| 36.00  | -77.80 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |
| 40.00  | -77.80 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |
| 40.00  | -77.80 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |
| 36.00  | -77.80 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |
| 96.00  | -77.80 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |
| 100.00 | -77.80 | 65.00 | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |
| 100.00 | -77.80 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |
| 96.00  | -77.80 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 1.00 | 0.00 | 0.00 |

% describe the room divider opposite bookshelves, by the cabinet

|       |       |       |       |      |      |      |        |       |      |      |
|-------|-------|-------|-------|------|------|------|--------|-------|------|------|
| 67.00 | 56.00 | 0.00  | color | 1.00 | 0.10 | 0.10 | normal | 0.00  | 1.00 | 0.00 |
| 67.00 | 56.00 | 78.00 | color | 1.00 | 0.10 | 0.10 | normal | 0.00  | 1.00 | 0.00 |
| 67.00 | -4.00 | 78.00 | color | 1.00 | 0.10 | 0.10 | normal | 0.00  | 1.00 | 0.00 |
| 67.00 | -4.00 | 0.00  | color | 1.00 | 0.10 | 0.10 | normal | 0.00  | 1.00 | 0.00 |
| 67.00 | 56.00 | 78.00 | color | 0.60 | 0.66 | 0.66 | normal | 1.00  | 0.00 | 0.00 |
| 69.00 | 56.00 | 78.00 | color | 0.60 | 0.66 | 0.66 | normal | 1.00  | 0.00 | 0.00 |
| 69.00 | 56.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 1.00  | 0.00 | 0.00 |
| 67.00 | 56.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | 1.00  | 0.00 | 0.00 |
| 67.00 | 56.00 | 78.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00 | 1.00 |
| 67.00 | -4.00 | 78.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00 | 1.00 |
| 69.00 | -4.00 | 78.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00 | 1.00 |
| 69.00 | 56.00 | 78.00 | color | 0.60 | 0.66 | 0.66 | normal | 0.00  | 0.00 | 1.00 |
| 67.00 | -4.00 | 78.00 | color | 0.60 | 0.66 | 0.66 | normal | -1.00 | 0.00 | 0.00 |
| 67.00 | -4.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | -1.00 | 0.00 | 0.00 |
| 69.00 | -4.00 | 0.00  | color | 0.60 | 0.66 | 0.66 | normal | -1.00 | 0.00 | 0.00 |

69.00 -4.00 78.00 color 0.60 0.66 0.66 normal -1.00 0.00 0.00

% describe the cabinet, a door

85.00 -4.00 0.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00  
85.00 -21.50 0.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00  
85.00 -21.50 78.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00  
85.00 -4.00 78.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00

% describe the cabinet, another door

85.00 -22.50 78.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00  
85.00 -22.50 0.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00  
85.00 -40.00 0.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00  
85.00 -40.00 78.00 color 0.60 0.60 0.60 normal 0.00 1.00 0.00

% describe the cabinet, the left side

85.00 -4.00 0.00 color 0.40 0.40 0.40 normal 1.00 0.00 0.00  
85.00 -4.00 78.00 color 0.40 0.40 0.40 normal 1.00 0.00 0.00  
103.00 -4.00 78.00 color 0.40 0.40 0.40 normal 1.00 0.00 0.00  
103.00 -4.00 0.00 color 0.40 0.40 0.40 normal 1.00 0.00 0.00

% describe the cabinet, the right side

85.00 -40.00 0.00 color 0.40 0.40 0.40 normal -1.00 0.00 0.00  
103.00 -40.00 0.00 color 0.40 0.40 0.40 normal -1.00 0.00 0.00  
103.00 -40.00 78.00 color 0.40 0.40 0.40 normal -1.00 0.00 0.00  
85.00 -40.00 78.00 color 0.40 0.40 0.40 normal -1.00 0.00 0.00

% describe the cabinet, the top

103.00 -40.00 78.00 color 0.40 0.40 0.40 normal 0.00 0.00 1.00  
85.00 -40.00 78.00 color 0.40 0.40 0.40 normal 0.00 0.00 1.00  
85.00 -4.00 78.00 color 0.40 0.40 0.40 normal 0.00 0.00 1.00  
103.00 -4.00 78.00 color 0.40 0.40 0.40 normal 0.00 0.00 1.00

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4 57 58 59 60  
4 61 62 63 64  
4 65 66 67 68  
4 69 70 71 72  
4 73 74 75 76  
4 77 78 79 80  
4 81 82 83 84  
4 85 86 87 88  
4 89 90 91 92  
4 93 94 95 96  
4 97 98 99 100  
4 101 102 103 104  
4 105 106 107 108  
4 109 110 111 112  
4 113 114 115 116  
4 117 118 119 120  
4 121 122 123 124  
4 125 126 127 128  
4 129 130 131 132  
4 133 134 135 136  
4 137 138 139 140  
4 141 142 143 144  
4 145 146 147 148  
4 149 150 151 152  
4 153 154 155 156  
4 157 158 159 160  
4 161 162 163 164  
4 165 166 167 168  
4 169 170 171 172  
4 173 174 175 176  
4 177 178 179 180  
4 181 182 183 184  
4 185 186 187 188  
4 189 190 191 192  
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4 197 198 199 200  
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### Appendix C. *Polhemus Field Tables*

| X Coord | Y Coord | Z Coord | X dir | Y dir | Z dir | twist |
|---------|---------|---------|-------|-------|-------|-------|
| -60.00  | 60.00   | 76.32   | 9.79  | -0.48 | -1.88 | 10.93 |
| -35.69  | 60.00   | 76.32   | 9.79  | -0.48 | -1.88 | 10.93 |
| -26.47  | 60.00   | 72.91   | 9.90  | -0.45 | -1.08 | 6.18  |
| -18.85  | 60.00   | 71.35   | 9.98  | -0.23 | -0.40 | 3.52  |
| -8.26   | 60.00   | 71.35   | 9.98  | -0.34 | -0.24 | 1.85  |
| -0.98   | 60.00   | 71.27   | 9.97  | -0.41 | -0.24 | 2.13  |
| 8.84    | 60.00   | 71.63   | 9.95  | -0.78 | -0.22 | 3.41  |
| 18.35   | 60.00   | 73.18   | 9.96  | -0.65 | -0.12 | 6.67  |
| 27.12   | 60.00   | 75.09   | 9.93  | -0.82 | 0.55  | 9.44  |
| 35.73   | 60.00   | 78.78   | 9.81  | -1.49 | 1.13  | 13.18 |
| 60.00   | 60.00   | 78.78   | 9.81  | -1.49 | 1.13  | 13.18 |
| -60.00  | 36.12   | 76.32   | 9.79  | -0.48 | -1.88 | 10.93 |
| -35.69  | 36.12   | 76.32   | 9.79  | -0.48 | -1.88 | 10.93 |
| -26.47  | 36.25   | 72.91   | 9.90  | -0.45 | -1.08 | 6.18  |
| -18.85  | 35.98   | 71.35   | 9.98  | -0.23 | -0.40 | 3.52  |
| -8.26   | 35.78   | 71.35   | 9.98  | -0.34 | -0.24 | 1.85  |
| -0.98   | 35.97   | 71.27   | 9.97  | -0.41 | -0.24 | 2.13  |
| 8.84    | 36.15   | 71.63   | 9.95  | -0.78 | -0.22 | 3.41  |
| 18.35   | 36.29   | 73.18   | 9.96  | -0.65 | -0.12 | 6.67  |
| 27.12   | 35.93   | 75.09   | 9.93  | -0.82 | 0.55  | 9.44  |
| 35.73   | 35.65   | 78.78   | 9.81  | -1.49 | 1.13  | 13.18 |
| 60.00   | 35.65   | 78.78   | 9.81  | -1.49 | 1.13  | 13.18 |

Table 1. Measured Polhemus position, direction, and twist

| X Coord | Y Coord | Z Coord | X dir | Y dir | Z dir | twist  |
|---------|---------|---------|-------|-------|-------|--------|
| -60.00  | 27.43   | 72.58   | 9.64  | -1.55 | 1.03  | 13.00  |
| -35.65  | 27.43   | 72.58   | 9.64  | -1.55 | 1.03  | 13.00  |
| -26.41  | 27.91   | 69.75   | 9.33  | -1.60 | 0.80  | 12.93  |
| -17.62  | 27.51   | 68.97   | 9.17  | -1.64 | 0.77  | 12.80  |
| -8.92   | 26.52   | 68.76   | 9.08  | -1.77 | 0.45  | 12.63  |
| 0.02    | 26.36   | 68.54   | 9.33  | -1.55 | 0.70  | 12.88  |
| 8.75    | 26.25   | 68.65   | 9.60  | -1.50 | 0.91  | 12.99  |
| 18.32   | 26.16   | 69.79   | 9.71  | -1.20 | 1.08  | 13.12  |
| 26.87   | 26.65   | 71.93   | 9.91  | -0.95 | 1.38  | 13.40  |
| 39.59   | 26.84   | 74.73   | 10.20 | -0.72 | 1.63  | 13.59  |
| 60.00   | 26.84   | 74.73   | 10.20 | -0.72 | 1.63  | 13.59  |
| -60.00  | 18.33   | 71.63   | 9.76  | -1.32 | -1.64 | 2.08   |
| -35.63  | 18.33   | 71.63   | 9.76  | -1.32 | -1.64 | 2.08   |
| -27.01  | 18.33   | 69.53   | 9.82  | -1.60 | -0.89 | 359.12 |
| -18.53  | 18.15   | 68.86   | 9.80  | -1.94 | -0.43 | 359.04 |
| -8.32   | 17.88   | 68.63   | 9.82  | -1.84 | -0.16 | 358.38 |
| 0.12    | 17.62   | 68.57   | 9.81  | -1.84 | -0.10 | 359.20 |
| 9.48    | 17.63   | 68.76   | 9.82  | -1.82 | 0.04  | 358.93 |
| 17.93   | 17.40   | 69.59   | 9.76  | -2.13 | 0.13  | 0.16   |
| 26.95   | 17.57   | 71.81   | 9.65  | -2.34 | 1.00  | 3.46   |
| 36.42   | 17.69   | 74.65   | 9.68  | -2.05 | 1.36  | 7.16   |
| 60.00   | 17.69   | 74.65   | 9.68  | -2.05 | 1.36  | 7.16   |

Table 2. Measured Polhemus position, direction, and twist (cont)

| X Coord | Y Coord | Z Coord | X dir | Y dir | Z dir | twist  |
|---------|---------|---------|-------|-------|-------|--------|
| -60.00  | 9.32    | 70.86   | 9.55  | -2.17 | 1.29  | 6.89   |
| -36.03  | 9.32    | 70.86   | 9.55  | -2.17 | 1.29  | 6.89   |
| -26.33  | 9.23    | 68.81   | 9.42  | -2.32 | 0.97  | 6.85   |
| -18.21  | 9.14    | 68.20   | 9.35  | -2.63 | 0.73  | 6.71   |
| -9.03   | 8.85    | 68.15   | 9.09  | -2.88 | 0.42  | 6.70   |
| 0.09    | 8.25    | 68.07   | 9.20  | -2.63 | 0.50  | 6.90   |
| 9.44    | 8.02    | 68.38   | 9.21  | -2.32 | 0.60  | 6.92   |
| 18.02   | 8.27    | 68.87   | 9.35  | -2.02 | 0.79  | 6.96   |
| 27.54   | 8.68    | 69.76   | 9.54  | -1.94 | 0.95  | 7.03   |
| 37.04   | 9.01    | 73.61   | 9.70  | -1.80 | 1.24  | 7.17   |
| 60.00   | 9.01    | 73.61   | 9.70  | -1.80 | 1.24  | 7.17   |
| -60.00  | 0.19    | 70.46   | 9.78  | -0.60 | -1.91 | 357.74 |
| -36.11  | 0.19    | 70.46   | 9.78  | -0.60 | -1.91 | 357.74 |
| -27.43  | 0.29    | 68.57   | 9.87  | -0.71 | -1.37 | 357.57 |
| -18.15  | 0.28    | 67.98   | 9.87  | -1.18 | -1.02 | 357.22 |
| -9.49   | 0.78    | 67.97   | 9.90  | -1.16 | -0.60 | 358.17 |
| 0.05    | 0.32    | 68.02   | 9.92  | -1.12 | -0.41 | 358.42 |
| 9.96    | -0.13   | 68.28   | 9.94  | -1.01 | -0.24 | 357.40 |
| 18.38   | 0.37    | 68.77   | 9.88  | -1.51 | -0.05 | 358.46 |
| 27.78   | 0.59    | 69.66   | 9.89  | -1.37 | 0.43  | 358.91 |
| 36.06   | 0.11    | 73.02   | 9.81  | -1.25 | 1.34  | 359.42 |
| 60.00   | 0.11    | 73.02   | 9.81  | -1.25 | 1.34  | 359.42 |

Table 3. Measured Polhemus position, direction, and twist (cont)

| X Coord | Y Coord | Z Coord | X dir | Y dir | Z dir | twist  |
|---------|---------|---------|-------|-------|-------|--------|
| -60.00  | -9.43   | 70.57   | 9.69  | -1.38 | 1.33  | 359.37 |
| -36.42  | -9.43   | 70.57   | 9.69  | -1.38 | 1.33  | 359.37 |
| -27.03  | -9.24   | 68.68   | 9.52  | -1.60 | 1.29  | 359.24 |
| -18.20  | -9.38   | 68.38   | 9.27  | -1.68 | 1.18  | 359.16 |
| -9.27   | -9.73   | 68.27   | 9.17  | -1.78 | 0.89  | 359.15 |
| 0.19    | -9.34   | 68.04   | 9.38  | -1.65 | 1.11  | 359.39 |
| 9.28    | -9.13   | 68.24   | 9.69  | -1.58 | 1.39  | 359.71 |
| 17.98   | -9.34   | 68.87   | 9.95  | -1.43 | 1.61  | 359.97 |
| 26.99   | -9.39   | 69.75   | 10.00 | -1.34 | 1.65  | 360.25 |
| 36.09   | -9.25   | 73.09   | 10.24 | -1.28 | 1.70  | 360.35 |
| 60.00   | -9.25   | 73.09   | 10.24 | -1.28 | 1.70  | 360.35 |
| -60.00  | -18.16  | 70.74   | 9.84  | -0.83 | -1.44 | 354.64 |
| -36.02  | -18.16  | 70.74   | 9.84  | -0.83 | -1.44 | 354.64 |
| -26.87  | -18.84  | 69.45   | 9.90  | -1.11 | -0.73 | 355.73 |
| -18.27  | -19.20  | 68.69   | 9.91  | -1.14 | -0.47 | 355.89 |
| -8.68   | -19.30  | 68.52   | 9.86  | -1.57 | -0.11 | 356.31 |
| -0.86   | -18.60  | 67.96   | 9.90  | -1.52 | 0.12  | 357.91 |
| 8.78    | -17.83  | 68.74   | 9.87  | -1.56 | 0.24  | 355.82 |
| 18.29   | -17.66  | 68.43   | 9.93  | -1.07 | 0.21  | 354.89 |
| 27.76   | -17.72  | 70.50   | 9.80  | -0.95 | 1.68  | 351.76 |
| 35.79   | -17.99  | 73.10   | 9.79  | -0.99 | 1.70  | 351.67 |
| 60.00   | -17.99  | 73.10   | 9.79  | -0.99 | 1.70  | 351.67 |

Table 4. Measured Polhemus position, direction, and twist (cont)



| X Coord | Y Coord | Z Coord | X dir | Y dir | Z dir | twist  |
|---------|---------|---------|-------|-------|-------|--------|
| -60.00  | -27.13  | 71.94   | 9.53  | -1.06 | 1.52  | 351.44 |
| -36.20  | -27.13  | 71.94   | 9.53  | -1.06 | 1.52  | 351.44 |
| -26.96  | -26.78  | 69.75   | 9.46  | -1.39 | 1.43  | 351.29 |
| -18.01  | -27.31  | 68.79   | 9.21  | -1.67 | 1.14  | 350.97 |
| -8.99   | -27.18  | 68.57   | 9.09  | -1.81 | 1.10  | 350.82 |
| -0.35   | -26.71  | 68.50   | 9.01  | -2.13 | 0.88  | 350.63 |
| 8.66    | -26.91  | 68.84   | 9.09  | -1.98 | 1.14  | 350.65 |
| 18.13   | -26.57  | 68.99   | 9.24  | -1.93 | 1.22  | 350.96 |
| 27.10   | -26.74  | 71.02   | 9.44  | -1.61 | 1.38  | 351.22 |
| 35.88   | -26.85  | 73.72   | 9.69  | -1.49 | 1.54  | 351.40 |
| 60.00   | -26.85  | 73.72   | 9.69  | -1.49 | 1.54  | 351.40 |
| -60.00  | -34.99  | 74.24   | 9.61  | -0.87 | -2.53 | 349.14 |
| -36.86  | -34.99  | 74.24   | 9.61  | -0.87 | -2.53 | 349.14 |
| -27.45  | -35.76  | 71.62   | 9.73  | -0.82 | -2.06 | 349.72 |
| -17.39  | -35.87  | 69.59   | 9.90  | -0.82 | -1.03 | 351.84 |
| -8.94   | -35.69  | 69.25   | 9.94  | -0.88 | -0.44 | 352.86 |
| 0.57    | -36.56  | 69.14   | 9.93  | -0.84 | -0.45 | 354.40 |
| 9.02    | -36.20  | 69.34   | 9.93  | -0.84 | -0.35 | 353.19 |
| 18.00   | -36.30  | 69.92   | 9.94  | -0.84 | -0.22 | 353.05 |
| 27.60   | -35.77  | 72.60   | 9.97  | -0.50 | 0.34  | 349.97 |
| 35.68   | -35.84  | 75.58   | 9.81  | -0.42 | 1.79  | 346.46 |
| 60.00   | -35.84  | 75.58   | 9.81  | -0.42 | 1.79  | 346.46 |

Table 5. Measured Polhemus position, direction, and twist (cont)

| X Coord | Y Coord | Z Coord | X dir | Y dir | Z dir | twist  |
|---------|---------|---------|-------|-------|-------|--------|
| -60.00  | -60.00  | 74.24   | 9.61  | -0.87 | -2.53 | 349.14 |
| -36.86  | -60.00  | 74.24   | 9.61  | -0.87 | -2.53 | 349.14 |
| -27.45  | -60.00  | 71.62   | 9.73  | -0.82 | -2.06 | 349.72 |
| -17.39  | -60.00  | 69.59   | 9.90  | -0.82 | -1.03 | 351.84 |
| -8.94   | -60.00  | 69.25   | 9.94  | -0.88 | -0.44 | 352.86 |
| 0.57    | -60.00  | 69.14   | 9.93  | -0.84 | -0.45 | 354.40 |
| 9.02    | -60.00  | 69.34   | 9.93  | -0.84 | -0.35 | 353.19 |
| 18.00   | -60.00  | 69.92   | 9.94  | -0.84 | -0.22 | 353.05 |
| 27.60   | -60.00  | 72.60   | 9.97  | -0.50 | 0.34  | 349.97 |
| 35.68   | -60.00  | 75.58   | 9.81  | -0.42 | 1.79  | 346.46 |
| 60.00   | -60.00  | 75.58   | 9.81  | -0.42 | 1.79  | 346.46 |

Table 6. Measured Polhemus position, direction, and twist (cont)

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## *Vita*

Captain Robert K. Rebo [REDACTED] He graduated from South Salem High School in 1972 and entered Brigham Young University in Provo, Utah. He served as a missionary for the Church of Jesus Christ of latter-day Saints from December 1973 through December 1975. He graduated from BYU in 1979 with a Bachelor of Science Degree in Computer Science. Captain Rebo entered Missile Combat Crew Initial Qualification Training in May of 1979. He graduated as a Distinguished Graduate and then served four years at Minot AFB, North Dakota as a Missile Launch Officer, Combat Crew Commander and Flight Commander. Captain Rebo then served as the Chief of the Systems Operations Branch at the Warrior Preparation Center, a Joint Wargaming Center in Einsiedlerhof, West Germany for three and a half years before entering the School of Engineering, Air Force Institute of Technology in June 1987. He is married [REDACTED] Rebo of Birkenhead, England [REDACTED]

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### *Abstract*

➤ This effort researches existing Helmet-Mounted Display (HMD) systems and presents a prototype design of a color Helmet-Mounted Virtual Environment Display System. Many existing systems are discussed, including systems currently in use by the US Navy, Air Force, and Army. Several differing designs are presented and evaluated.

The Air Force Institute of Technology Helmet-Mounted Virtual Environment Display System places the user in an visual situation that is generated by a computer. This HMD system could easily be adapted for use with a video camera.

This paper presents an inexpensive system design that incorporates the benefits of other efforts. The cost trade offs are evaluated and the best design for the lowest cost is presented. The optics, three dimensional considerations, the mounting platform and display technologies are also discussed. The final HMD system design is described in detail and presented so that any reader could build a similar system for minimal cost. This system uses color Liquid Crystal Displays (LCD) mounted directly before the eyes of the user. Specially designed optics were developed to enable the user to focus on the image only inches away. The positional information of the user is determined by a sensitive electro-magnetic device developed by Polhemus Navigational Sciences. This system is very accurate but has a limited effective range. Predictive tracking is discussed and implemented using a simple Kalman filter equation. Thesis. (SDO) ➤

The HMD system is designed to be mounted on any type of head gear. The principle mounts are an inexpensive bicycle helmet and an aircraft helmet.

The goal of this effort was to build a simple, inexpensive color helmet-mounted display (HMD) system that places the user in a visual virtual world.