# Augmented Reality: An Application of Heads-Up Display Technology to Manual Manufacturing Processes

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**Abstract**

We describe the design and prototyping steps we have taken toward the implementation of a heads-up, see-through, head-mounted display (HUDSET). Combined with head position sensing and a real world registration system, this technology allows a computer-produced diagram to be superimposed and stabilized on a specific position on a real-world object. Successful development of the HUDset technology will enable cost reductions and efficiency improvements in many of the human-involved operations in aircraft manufacturing, by eliminating templates, formboard diagrams, and other masking devices.

## The Manufacturing Problem

Someone once said that a Boeing 747 is not really an airplane, but five million parts flying in close formation. Modern airliners are complex machines that require a tremendous amount of manual effort to manufacture and assembly. The production of an airliner does not lend itself to complete automation for two reasons: first, because of the small lot size of parts. In many cases the average lot size for a part is less than ten. Second, automation is not practical in many cases because of the skills required to perform a task. Robots can not today provide the dexterity and perception of a human required to assemble many of the components of this product. In addition, the reprogramming costs for robotic systems are exacerbated by the small lot sizes. For these reasons, people continue to play a major role in the manufacture and assembly of modern aircraft.

Even so, aircraft are becoming more and more complex, as are their manufacturing processes. People in the factories are required to use an increasing amount of information in their jobs. Much of this information is derived from engineering designs for parts and processes stored in CAD systems. In many cases, this information comes to the factory floor in the form of assembly guides, templates, mylar drawings, wiring lists, and location markings on sheet metal. Occasionally, a PC screen will be used to indicate the next step in a process, or the next location to be connected. A significant source of expense and delay in aircraft manufacturing comes from the requirement to mirror changes in the engineering design in the guides, templates and so on used to control the manufacturing processes. If manufacturing workers were able to directly access digital CAD data when performing manufacturing or assembly operations, several sources of expense and error would be eliminated.

In this paper, we introduce technology to provide this access. The general concept is to provide a "see-thru" virtual reality goggle to the factory worker, and to use this device to augment the worker's visual field of view with useful and dynamically changing information.

### Augmented Reality

The enabling technology for this access interface is a heads-up (see-thru) display head set (we call it the "HUDset"), combined with head position sensing and workplace registration systems. This technology is used to "augment" the visual field of the user with information necessary in the performance of the current task, and therefore we refer to the technology as "augmented reality" (AR). For example see Figure 1, where a user looks at a workpiece, and sees the exact 3D location of a drill hole is indicated by a bright green arrow, along with the drill size and depth of the hole specified in a text window floating next to the arrow. As the user changes his perspective on the workpiece, the graphical indicator appears to stay in the same physical location. This is accomplished by tracking the six degrees of freedom of the head and transforming the graphics to compensate for changes in location and view orientation.

A primary difference between what we have begun referring to as "full" virtual reality (VR) and this "augmented reality" concept is in the complexity of the projected graphical objects. In our system, only simple wire frames, template outlines, designators, and text are displayed and animated. An immediate result of this difference is that augmented reality systems can be driven by standard and inexpensive microprocessors, since PC class processors have the computational power to transform and plot simple graphics in real time. Unlike full VR, the computer is not required to generate graphics for every pixel the user sees; the computer is only responsible for superimposing approximately 50 or fewer lines on the user's still-visible actual surroundings.

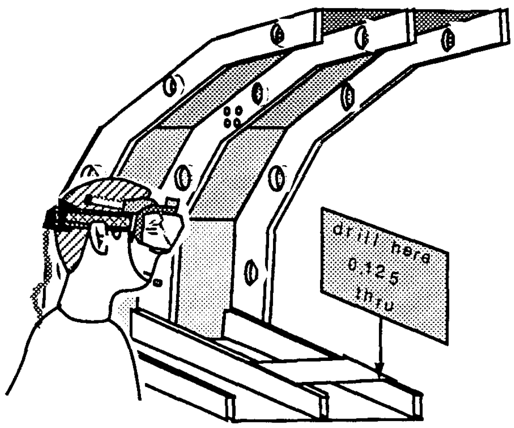


**Figure 1. An application where the HUDset is used to dynamically mark the position of a drill/rivet hole inside an aircraft fuselage.**

Some AR system requirements are more stringent than in the case of full VR, however. In particular, AR systems require accurate registration with the physical world. The level of accuracy required is application dependent. The location of the HUDset relative to the person's eyes and the workplace must be determined before work can begin. Since the HUDset can move around on the head, methods must exist to detect loss of registration and to allow re-registration during the work period.

The volume over which a user must be tracked is also application dependent. For a task performed at a table or desk, like the composite layup operation illustrated in Figure 2, short range devices using magnetic fields or camera image tracking will be sufficient. When a worker wearing a HUDset climbs into a wing section to drill a rivet hole, a long-range and, ideally, untethered tracking system will be necessary. Hybrid systems using two or more tracking technologies will span the gap between these extremes.

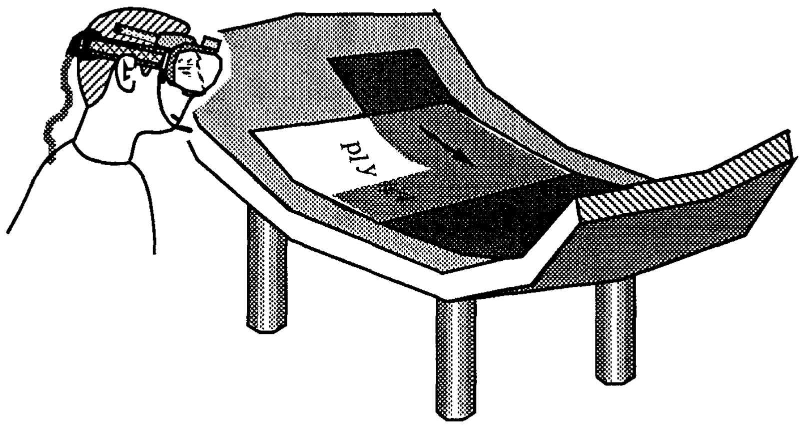


**Figure 2. An application where the HUDset is used to project graphical templates for the location and orientation of composite cloth during the layup process.**

## HUDset Technologies

Heads-up display technology has been with us for more than 20 years (Furness), the traditional application being fighter pilot situation displays. The basic elements of such a system, illustrated in Figure 3, are an image source, relay optics, and a beamsplitter. The beam splitter allows the user to see the real world and the graphics simultaneously. The relay optics generates a virtual image of the source at infinity focus. These components are usually part of the front windscreen of a fighter aircraft, but can also be part of a head-mounted display system. The later system keeps the situation display in front of the pilot independent of head position.

The first head-mounted display to incorporate head position sensing in order to stabilize the projected graphics on a real-world scene was built and experimented with by Ivan Sutherland (Sutherland). Sutherland's display used half-inch monochrome CRTs and half-solvered mirrors. In 1985, Warren Robinett and his colleagues at the University of North Carolina built a see-through display using color LCD displays, half-silvered mirrors, and magnifying lenses (Holloway, Robinett & Rolland). The UNC group is now designing another see-through head-mounted display with custom optics. They foresee the eventual use of this technology in a variety of applications, including some similar to the manufacturing operations on which our work is focused.

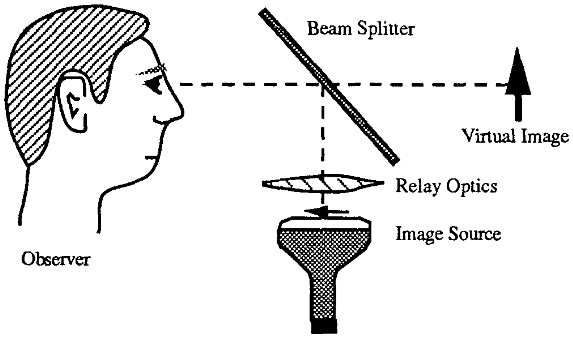


**Figure 3. The basic components of a HUD system, including an image source, an relay lens system, and a beam splitter.**

The requirements on a military HUD system are similar to those of the industrial HUDset. Both systems must be ruggedized and safe to use. The HUDset requires extended head tracking, but no eye or cornea tracking. The industrial application requires a wide field of view, but a relatively low pixel resolution. Only one color is needed in the HUDset, which greatly eases the constraints on the relay optics that bring the graphical images into the eye.

Figure 4 shows a drawing of what an industrial HUDset might look like. In order to keep the headgear as light as possible for the sake of wearer comfort, the display system's processor, memory and power source would be configured as a belt pack. At the beginning of a task, the user would download the CAD/CAM data into the processor. This could occur at the recharging station for the system's batteries. Alternatively, packet radio could be used to download CAD/CAM data on the fly. The user would interact with the data through simple voice commands or a manual device on the hip-mounted processor, to change the display when new information is needed.

Our research and development project at Boeing is aimed at advancing the components of this technology to the point at which the use of AR in manufacturing applications is practical. The two main thrusts of the project are to improve the accuracy with which a diagram can be "projected" onto a real-world position, and to increase the range over which a user's head position and orientation can be accurately sensed and measured. We are prototyping HUDset systems similar to that depicted in Figure 4 and experimenting with a variety of position sensing technologies.

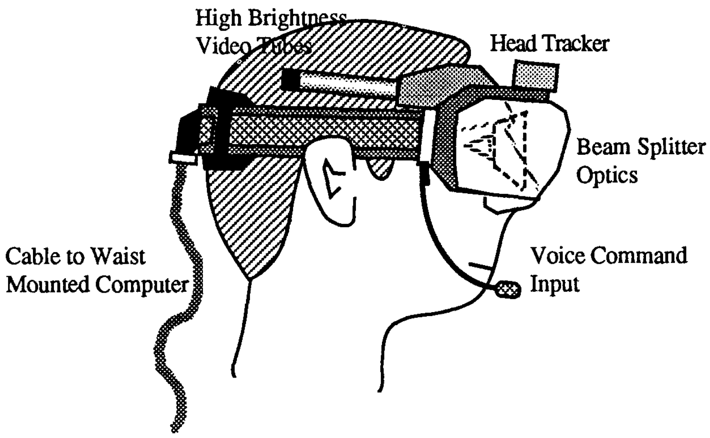


**Figure 4. A drawing of the components of a HUDset. The video tubes provide high brightness VGA graphics that are folded into the users line of sight with beam splitting relay optics. The head is tracked in six degrees of freedom. Interaction with the control software may occur through voice input if ambient conditions permit.**

## A Demonstration System

As a proof of concept, we have built a simple system that demonstrates the application of augmented reality to manufacturing. To roughly approximate the characteristics of a HUDset, we used a headmounted PC display called the Private Eye (Reflection Technologies). This commercially available device weights only a few ounces, and places a virtual 720x280 pixel CGA PC screen at a comfortable reading distance in front of the wearer. To the headband of this display we have attached the receiver unit of a Polhemus 3D Isotrack system (Polhemus), which uses alternating magnetic fields to calculate at up to fifty times a second the six degrees of freedom of the receiving unit's position and orientation relative to the transmitting unit.. Both of these devices interface to a standard Intel 386-based microcomputer system. The transmitter of the tracking system is rigidly attached to the demonstration base platform.

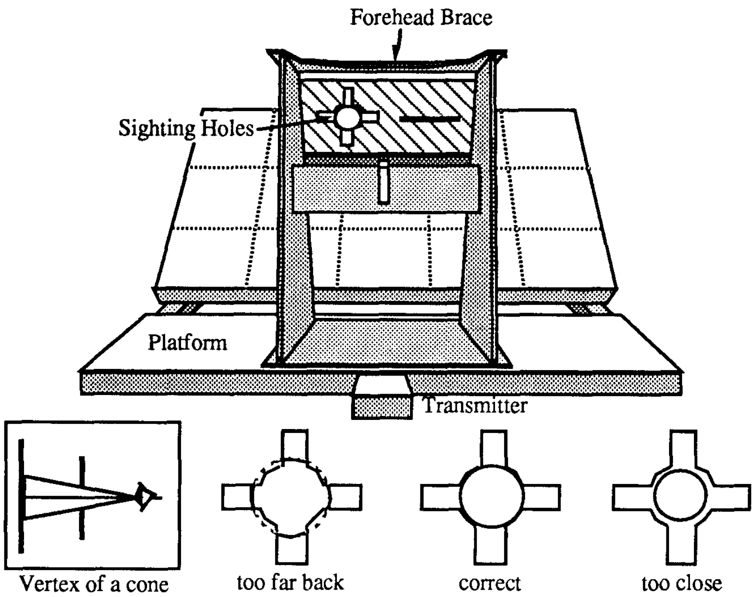


**Figure 5. The demonstration platform with 3D tracker transmitter and the calibration device used to locate the position of the left eye relative to the work platform. The insets illustrate how the eye's position is located in space.**

The platform can be seen in Figure 5 with the prototype of a registration device kinematically mounted on its surface. This device is used at the beginning of the session to locate the position of the eye relative to the head mounted position sensor. The user adjusts her head position until two circles and two lines each coincide. This places her left eye at the apex of a cone whose coordinates are known relative to the Polhemus transmitter and levels the tilt of the head. The controlling software records the position and angles of the receiver at this point. These registration offsets are used in the graphics coordinate transformation routines to accurately calculate the user's view of graphical objects from any point near the platform. After registration, this device is removed from the platform.

Four applications have been developed for this demonstration system, illustrated in Figure 6. The first of these is the *wiring formboard*, where wire bundles are manufactured by laying individual wires across pegs on an annotated board. In today's factory, the board is annotated with a long, computer-generated plot of the wire bundle glued to sheets of plywood. The assembly worker must be able to read the paper drawing as the bundle grows. For this demonstration, a blank peg board represents the formboard. The computer indicates the position of the pegs for the current wire bundle assembly task for the user to install. After this, the paths of individual wires are indicated sequentially on the board as a series of bright red lines.

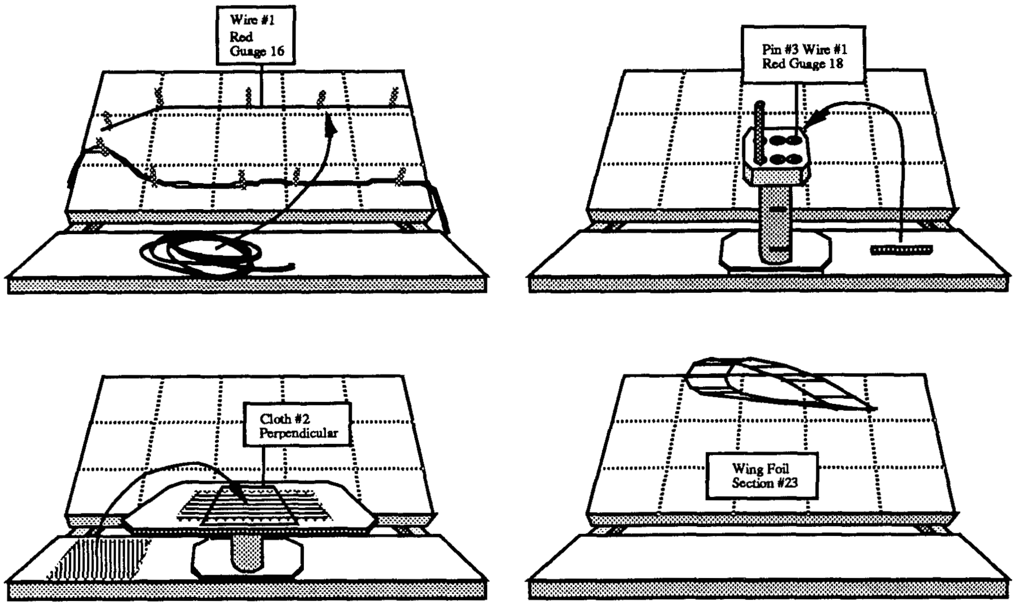


**Figure 6. Four applications demonstrated with the Private Eye based system. Clockwise from top-left: wiring formboard, wiring connector assembly, composite cloth layup, and wire frame display and animation.**

The second application is *connector assembly.* After the wire bundle is assembled, the ending leads are inserted into a multipinned connector. The factory worker must consult a paper "map" of assignments, telling what wire goes into which pin. For the larger connectors, as many as fifty wires are mapped to pins, an error-prone task. In this demonstration, a red indicating line appears to protrude from the connector at the exact location where the current wire is to be inserted. A text window tells the user the number and description of the correct wire. The user moves to the next wire by again hitting the space-bar on the keyboard.

The third application is composite cloth layup. During the manufacture of composite structures, the worker must lay precut sheets of sticky fabric in an exact orientation and location on the surface of a layup tool mandril. Currently, a physical template is laid over the tool and the location of the sheet marked through with a grease pencil. Automated techniques available today use either laser designators or robotic ink jets to mark the composite. In this demonstration, the shape, location, and orientation of the sheet is indicated by a bright red outline on the tool or on the previously-placed layer of composite cloth. The user moves to the next cloth's outline projection by again hitting the space-bar on the keyboard.

The final application in this demonstration system is maintenance or assembly. The process of removing a part from an aircraft for servicing is made difficult by the compactness of the machinery. Often there is one and only one way to remove a part, involving a sequence of twists and turns to avoid intervening tubing and structural members. In this demonstration, we show how the wire frame of a 3D part can be visualized in space. This wire frame can be first superimposed over the part to be removed, and then animation to show the user the exact egress path in 3D repeated in a movie loop. The reverse process can be used for the assembly of complex subassemblies. For this demonstration, a cube and an airfoil were formed in the space above the platform to illustrate 3D part visualization.

This demonstration system has several significant weaknesses. First, the Private Eye is not intended for metrology applications. The eyepiece is not rigidly mounted to the headset, making it difficult to maintain alignment. Second, this system is not truly "see thru", counting on the brain to fuse the left eye view of the real scene with the virtual image of the graphics visible only to the right eye. Many people have trouble with this, particularly those with some degree of amblyopia. Third, the field of view of the Private Eye is only ±7 degrees, giving the impression of looking at the graphical image through a cardboard tube. The user must explore the graphical world by moving his head around instead of moving his eyes. Many people have trouble with this, too. Fourth, there exists a time lag between the motion of the head and a change in the graphics. We are currently investigating a hypothesis that a more careful tuning of the software that interfaces the PC with the Polhemus system would largely eliminate this lag.

Even with these weaknesses, however, the system has been well received and accomplishes the goal of demonstrating the potential of this technology for manufacturing applications. As an intermediary between the Private Eye system just described and a full set of see-through goggles, we have built a see-through Private Eye goggle. Pictured in Figure 7, the eyepiece of the Private Eye has been rotated to face downward and moved up to the forehead area. A dichroic beam splitter redirects the graphics image into the users eye, while allowing an unobscured view of the work piece. This type of beam splitter reflects the red light of the Private Eye image, while allowing transmission of most all other wavelengths from the outside world. This new system still has a limited field of view, but will allow the development of registration devices and methods required for see-through applications.

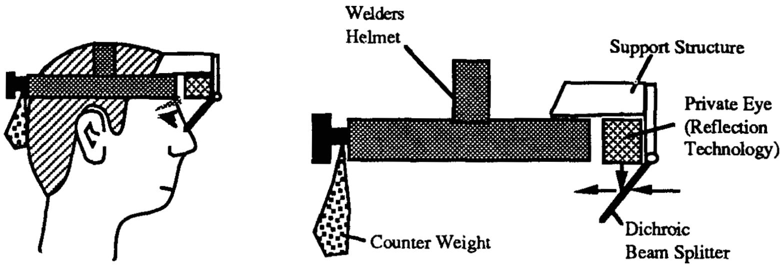


**Figure 7. A drawing of a newly constructed see-through Private Eye based headset. The graphics produced for the eyepiece must be inverted to give a properly oriented image.**

## Discussion

We expect an increasing number of manufacturing applications to become feasible as both position sensing range and diagram positioning accuracy continue to improve. Table 1 gives the short list of applications that we are currently considering, as well as their required range and accuracy. Several of these depend on position sensing technology that is currently beyond the state of the art. In fact, the position sensing technology is the ultimate limitation of AR, controlling the range and accuracy of possible applications.

| Task | Accuracy (in) | Range (ft) |
|---|---|---|
| Connector Assembly | 0.05 | 2 |
| Electronic Panel Assembly | 0.1 | 2 |
| Electronic Testing | 0.1 | 2 |
| Maintenance | 0.25 | 5 |
| Kevlar Duct Layup | 0.2 | 5 |
| Composite Layup | 0.1 | 10 |
| Mandrel Measurement | 0.25 | 10 |
| Formboard | 0.2 | 30 |
| Structural Riveting | 0.05 | 400 |

**Table 1. A short list of applications of AR to manufacturing. The second and third columns give the estimated accuracy and range over which a user would need to be tracked.**

In some cases, with minor modification of existing technology, extended position tracking can be easily accomplished. As is shown in Figure 8, a "cellular" system is being developed for long slender volumes, such as the wiring formboard. As the worker moves along the formboard, she remains within range of one or more overlapping magnetic transmitting units. The computer selects and reads from the unit with the smallest distance to the receiver, mounted on the user's head. As the user moves, the computer hands off tracking from unit to unit, keeping only one transmitter active at a time. These types of tricks will allow a number of large volume, medium accuracy applications to be developed in lieu of a future, more general purpose tracking system, possibly one based on solid-state nanoaccelerometers (Kaiser 1991).

Finally, there remains the issue of registration calibration in the factory environment. Even the lightest-weight HUDset will eventually move on the wearer's face, producing registration errors in the graphics and the workpiece. Although research continues in this area, there are approaches under development for rapid re-registration that will partially ameliorate this problem using "glance and adjust" fiducials. These combine alignment graphics and simple calibration devices to allow the user to quickly correct for small registration errors in the field.

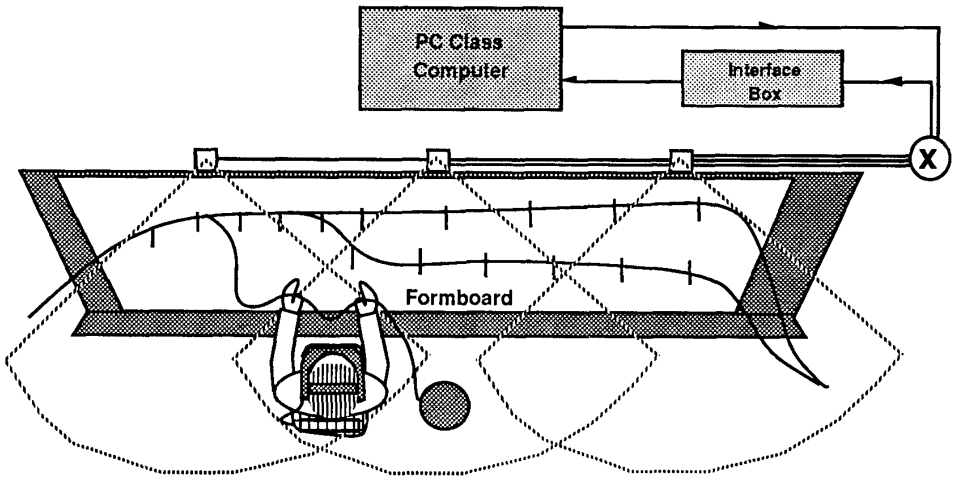


**Figure 8. The wiring form board application where the user has an extended range of operation. The magnetic transmitters are switched on as the user enters their effective range.**

## Conclusions

Fabrication and assembly in the aerospace industry are still dominated by complex, human-involved processes. Many processes involve systems of measurement templates, diagrams, and marking devices to superimpose information on workpieces. In this paper, we have described the use of head-mounted display technologies to improve the efficiency and quality of human workers in their performance of manufacturing activities. This technology is used to augment the visual field of the user with information necessary in the performance of the current task. The enabling technology is a heads-up display headset, or HUDset, incorporating with head position sensing and real world registration systems. A primary difference between virtual reality and "augmented reality" is in the complexity of the projected graphical objects. In our system, only simple wire frames, template outlines, designators, and text are displayed. An immediate result of this difference is that augmented reality systems can be driven by standard and inexpensive microprocessors. A prototype system is currently under development that will provide stereo video images over a wide field of view. Although applications of this technology is limited primarily by extended tracking technology, many near term applications are possible.


## Acknowledgements

The authors would like to thank Karl Embacher for creative input to and enthusiasm for this work, and the efforts of Michael MacIntire and Henry Sowizral in the development and refinement of the demonstration system.


## References


Furness, T. "Helmet-Mounted Displays and their Aerospace Applications", National Aerospace Electronics Conference, Dayton, OH, May 1969.

Holloway, Richard L., "Head-mounted display technical report," Technical Report #TR87-015, Dept. of Computer Science, University of North Carolina, Chapel Hill.

Product literature, 1990, Reflection Technologies, Inc., 240 Bear Hill Road, Waltham, MA 02154.

Product literature, 1990, Polhemus Inc., P.O. Box 560, Colchester, VT 05446.

Robinett, Warren and Rolland, Jannick P., "A computational model for the stereoscopic optics of a head-mounted display," Technical Report #TR91-009, Dept. of Computer Science, University of North Carolina, Chapel Hill.

Sutherland, Ivan E., "A head-mounted three-dimensional display," 1968 Fall Joint Computer Conference, AFIPS Conference Proceedings **33**, 757-764 (1968).

Kaiser, W., private communication, Jan. 1991