S1-60
6240

THE DESIGN OF PICTORIAL INSTRUMENTS

Stephen R. Ellis
NASA Ames Research Center
Moffett Federal Airfield, CA

INTRODUCTION

During the last twenty years, researchers at Ames have been investigating the design of pictorial displays for civilian aerospace applications. In the mid-1980's this work sparked public imagination with the suggestion that the experience of a virtual environment provided by a head-mounted aircraft simulator could be adapted inexpensively for a wide variety of other applications. It was suggested that these head-mounted devices, called by Ivan Sutherland the "ultimate computer display," could become the ultimate computer interface. They were thought to be able to take computer users beyond the two-dimensional desktop metaphor for computer operation into a three-dimensional environment metaphor. They were billed as the "disappearing" interface, but as is currently clear, they are still far from "disappeared" (Ref. 1).

One may get a sense of the background of some of this work at Ames by very briefly reviewing its development through a few examples of studies of human performance using interactive graphical displays. The essence of this work is human interface design. The characteristic innovation is that the interface itself appears as an environment. The goal has been to use this new format to advance the safety and efficiency of human-machine interfaces in commercial aircraft and spacecraft, and such applications have materialized (Refs. 2 and 3); but other applications can extend far beyond those in aerospace.

In the course of this work the researchers at Ames have followed the long standing interest people have had in pictures as a communication medium. Pictorial representations have both symbolic and geometric components. The Lascaux Cave art, probably the oldest pictures known, emphasizes the original, probably primal interest in symbolism. But pictures also make more quantitative points. Maps are a form of pictorial representation in which the geometry is central since the message is more numerical, but we can see that even mapmakers cannot resist decorating their creations with symbols.

As the graphics capability of portable computers advanced, it became possible in the 1980's to consider pictorial display formats for electronic displays in aircraft and spacecraft. At that time investigations began of the design of aircraft traffic displays incorporating perspective projections.

The intuitive and immediate comprehensibility of such displays made them attractive for situations requiring quick interpretation; but study of them rapidly shows that effective communication requires much more than visual impact and, in particular, that the well known ambiguities of perspective images have to be counteracted (Ref. 4).

In fact, research and implementation of reference systems at Ames has determined that considerable geometric and symbolic enhancement was necessary to make a perspective-based picture useful as a display for guidance and control (Refs. 5 and 6). The aircraft display shown in Fig. 1 (lower right) is not just a pretty picture. Some of the enhancements that transform it from what one could call a spatial display into a spatial instrument, a display designed for a purpose, are described in the caption.

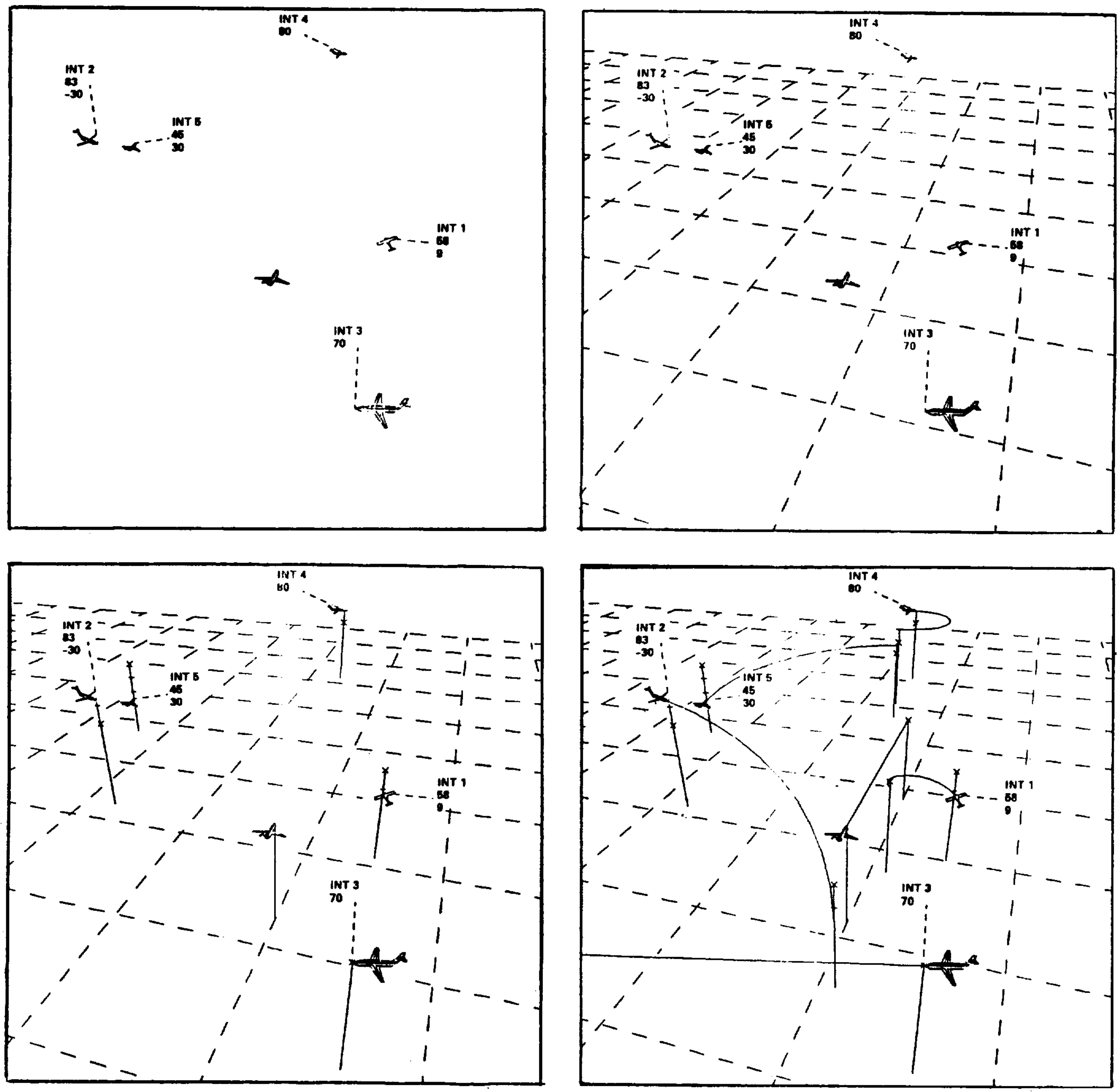

Figure 1 - Simply rendering an aircraft traffic pattern in perspective relative to a reference aircraft (center of display) does not in itself provide much spatial sense of the layout (upper left). Adding a reference grid helps but relative altitude is still hard to perceive (upper right). Adding drop-reference lines and coaltitude "x's" to show the reference aircraft's altitude against all others helps, but aircraft aspect is still ambiguous (lower left). Adding predictor lines with additional drop reference lines helps remove aspect ambiguity and resolve future traffic conflicts (lower right).
See Refs. 5 and 6 for more details.

Thus, as drawn by our E&S Picture System this display had many physically unrealizable characteristics, called geometric enhancements. These enhancements turned the display into an instrument. They allowed pilots to easily use the display to correct flight path errors, despite difficulties associated with rendering. Perspective ambiguities were only one such problem considered. But another way to avoid some of the uncertainties associated with perspective images is to jump into the picture itself.

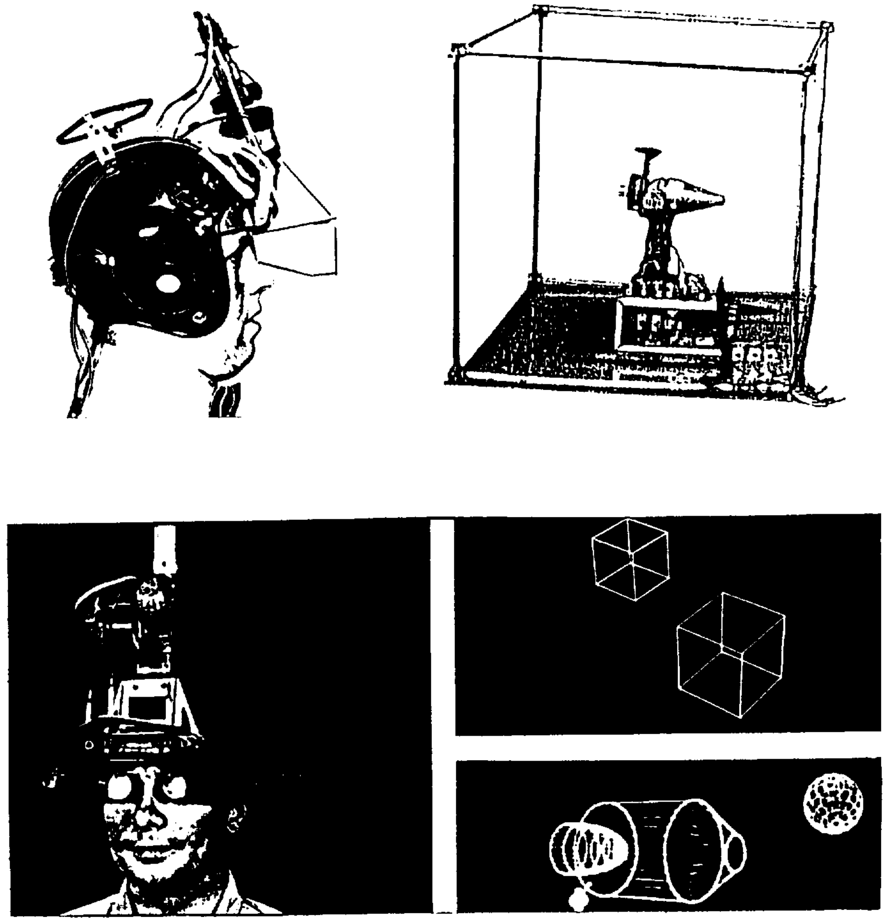

Figure 2 - Visual virtual environment display systems have three basic parts: a head-referenced visual display, head and/or body position sensors, a technique for controlling the visual display based on head and/or body movement. One of the earliest systems of this sort developed by Philco engineers (Ref. 7) used a head-mounted, binocular, virtual image viewing system, a Helmholtz coil electromagnetic head orientation sensor, and a remote TV camera slaved to head orientation to provide the visual image. Today this would be called a telepresence viewing system (upper left panel). It was used to control a remote camera (upper right panel) that was controlled by the user's head position. The first system to replace the video signal with a totally synthetic image produced through computer graphics was demonstrated by Ivan Sutherland for very simple geometric forms (lower panels) (Ref. 8).

The first implementation of a display system that allowed a viewer to do this is illustrated here in a figure from the early 1960's (Fig. 2). It was built by two Philco engineers, Brian and Comeau (Ref. 7).

This device illustrates the now familiar components of all subsequent systems using head-referenced displays. Sensors to monitor body positions, i.e., head and hand position trackers, effectors to present visual information, i.e., a miniature video display with accommodative relief, and some interlinkage hardware to connect the other two components.

These components combine in an active control loop which gives users the impression that they are located at a remote work site (Fig. 3).

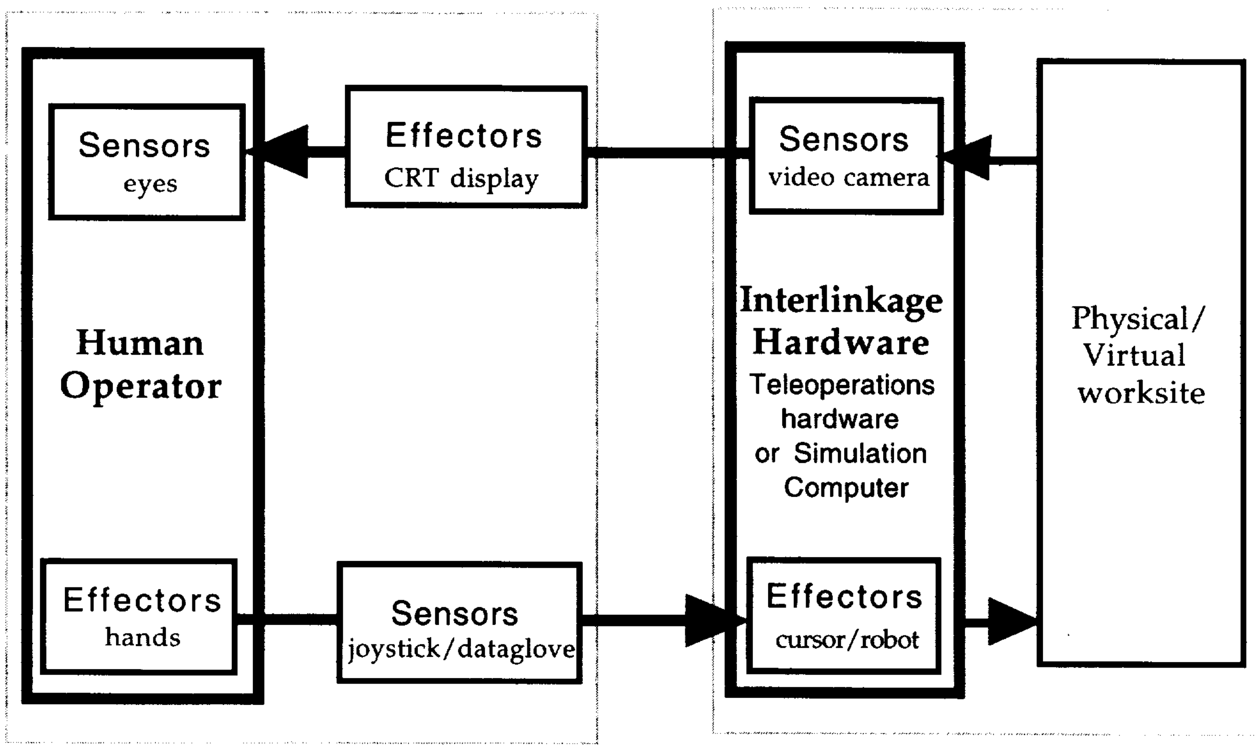

Figure 3 - Information flows in a virtual environment simulation or telepresence display.

In the case of a telepresence display the interlinkage hardware includes cameras and manipulators; this work site is real, but it could well be synthetic if the interlinkage hardware were a computer simulation.

Thus, a central aspect of head-referenced display systems is that they amount to personal simulators. Often they are simulators that are worn rather than entered. Accordingly, among the first operational display systems of this sort were indeed, head-mounted aircraft simulators (see Fig. 4).

Unlike traditional simulators associated with vehicular activity, the wearable systems are probably more uniquely suited for the simulation of manipulative activity like that associated with teleoperation. In particular, we have been interested in the study of the design of direction and distance in head-mounted displays of nearby objects; that is, objects within arms length. This application domain is relatively new since most head-mounted displays heretofore used in aerospace applications present virtual image targets at least several meters away from the user.

As an example of current design issues, we have studied the benefits of incorporating head-roll tracking for accurate presentation of direction and orientation information in a virtual environment. The need to include roll tracking is interesting since we could achieve shorter transmission and processing lags if it is left out.

Figure 4 - Though very expensive, the CAE Fiber Optic Helmet Mounted display, FOHUD (upper panel), is one of the highest-performance virtual environment systems used as a head-mounted aircraft simulator display. It can present an overall visual field 162° x 83.5° with 5-arcmin resolution with a high resolution inset of 24° x 18° of 1.5 arcmin resolution. It has a bright display, 30 Foot-Lambert, and a fast, optical head-tracker, 60-Hz. sampling, with accelerometer augmentation.

In our experiment we slaved a stereo camera platform having three degrees of rotational freedom to a head-mounted display. We studied the user's ability to position and orient objects in the control site to corresponding objects in the remote site (Fig. 5). Despite assertions of the benefits of matching human head kinematics through roll tracking, pitch and yaw were enough. We found that disabling roll had very little effect on performance provided subjects were not required to make very large rotations of their head with respect to their torso (Ref. 9).

In another example, we have studied perceptual issues that effect the apparent depth of nearby virtual objects presented via head-mounted displays called electronic haploscopes. They allow flexible control of the optical characteristics of binocular stimuli that may be optically superimposed in the subject's view. With this display a computer graphics image of a virtual object can be precisely calibrated so that factors that affect its apparent depth with respect to its intended depth may be studied.

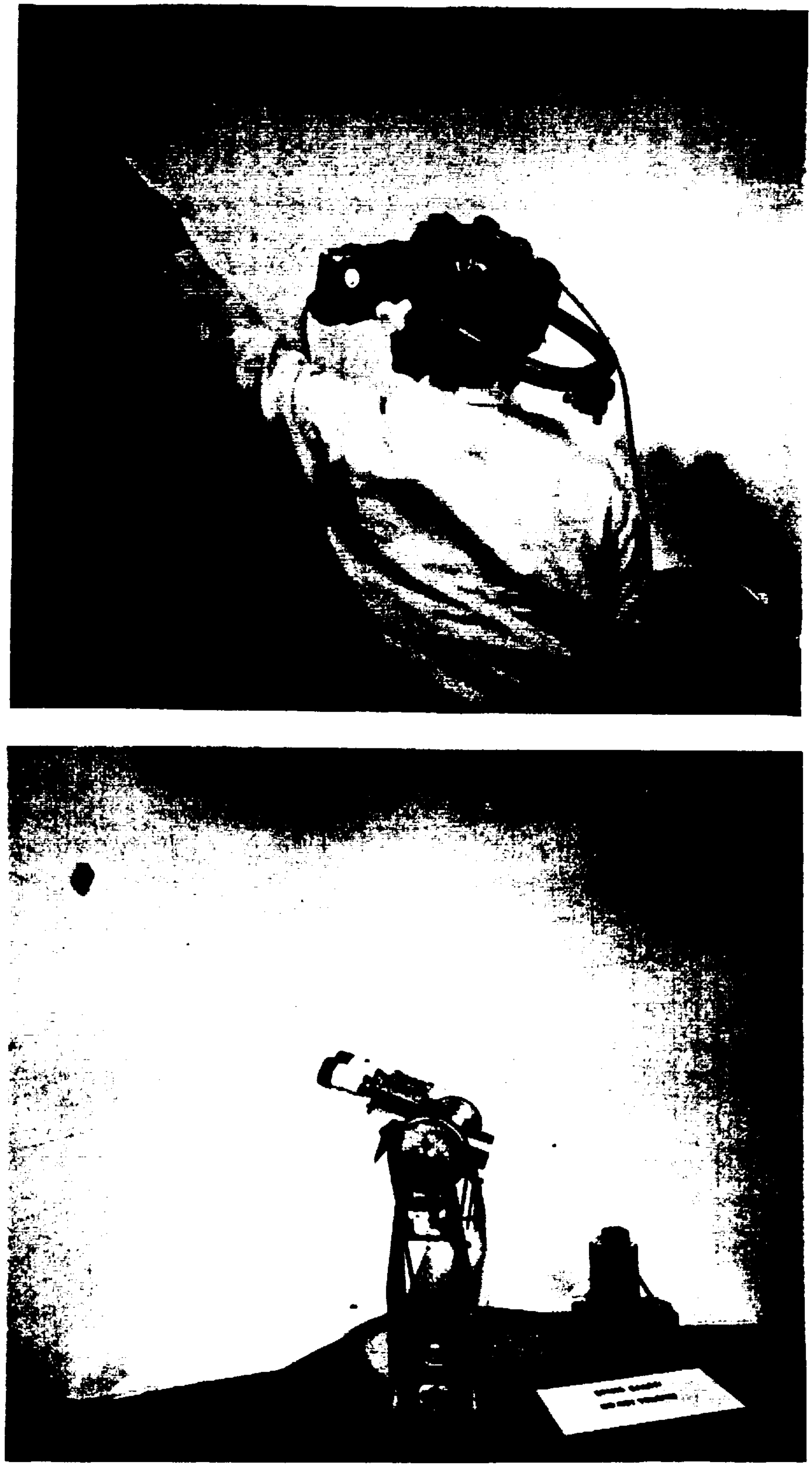

Figure 5 - The upper panel shows a three dof camera platform which is slued to the head orientation of a head-mounted display at the control site (lower panel). Studies of the improvement of the users' abilities to position and orient objects at the control site to match objects at the remote site have shown that the addition of camera roll only improves performance if large head rotations relative to the torso are forced. Pitch and yaw are usually sufficient.

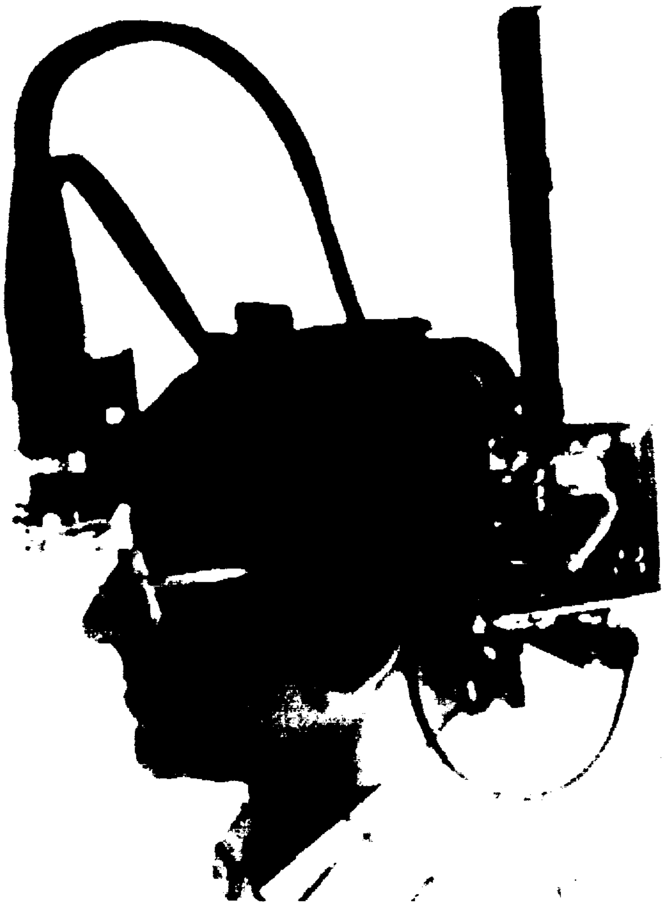

Figure 6 - An example of a head-mounted see-through display with adjustable viewing optics that allows independent variation in ocular vergence and accommodative demand making it an electronic haploscope.

Most recently, study has focused on an interesting interaction between the apparent distance to the virtual object and real surfaces over which it is superimposed. Briefly, we find that after graphics calibration and alignment, the apparent distance of the virtual object, as indicated by adjustment of a real cursor, is reduced by superposition on a real surface at the apparent distance of the object. This phenomena has clear implications for placement of virtual objects in displays for medical visualization, teleoperation and mechanical assembly. Current work is directed to describe it and to understand its cause (Ref. 10).

As part of interest in the dynamic aspects of the simulation loop, studies have been done on the intrinsic response latency of sensors and future studies on the role of latency, and update rates are planned for a number of perceptual and manual control phenomena, including the apparent offset of depth just mentioned.

In conclusion, it is useful to recall an observation about human interaction with pictorial displays developed from our research on the design of aerospace instruments. The phenomena most useful for the design of efficient pictorial displays are not invariably associated with the realistic rendering of the images, but rather the display and control of error. In some respects a sense of presence is not the central communication of our images. Display images, like maps, are schematic pictures with a point, often a numerical point. The principle challenge of designing them is often to determine how to portray error in a quickly interpretable manner so corrective action can be taken.

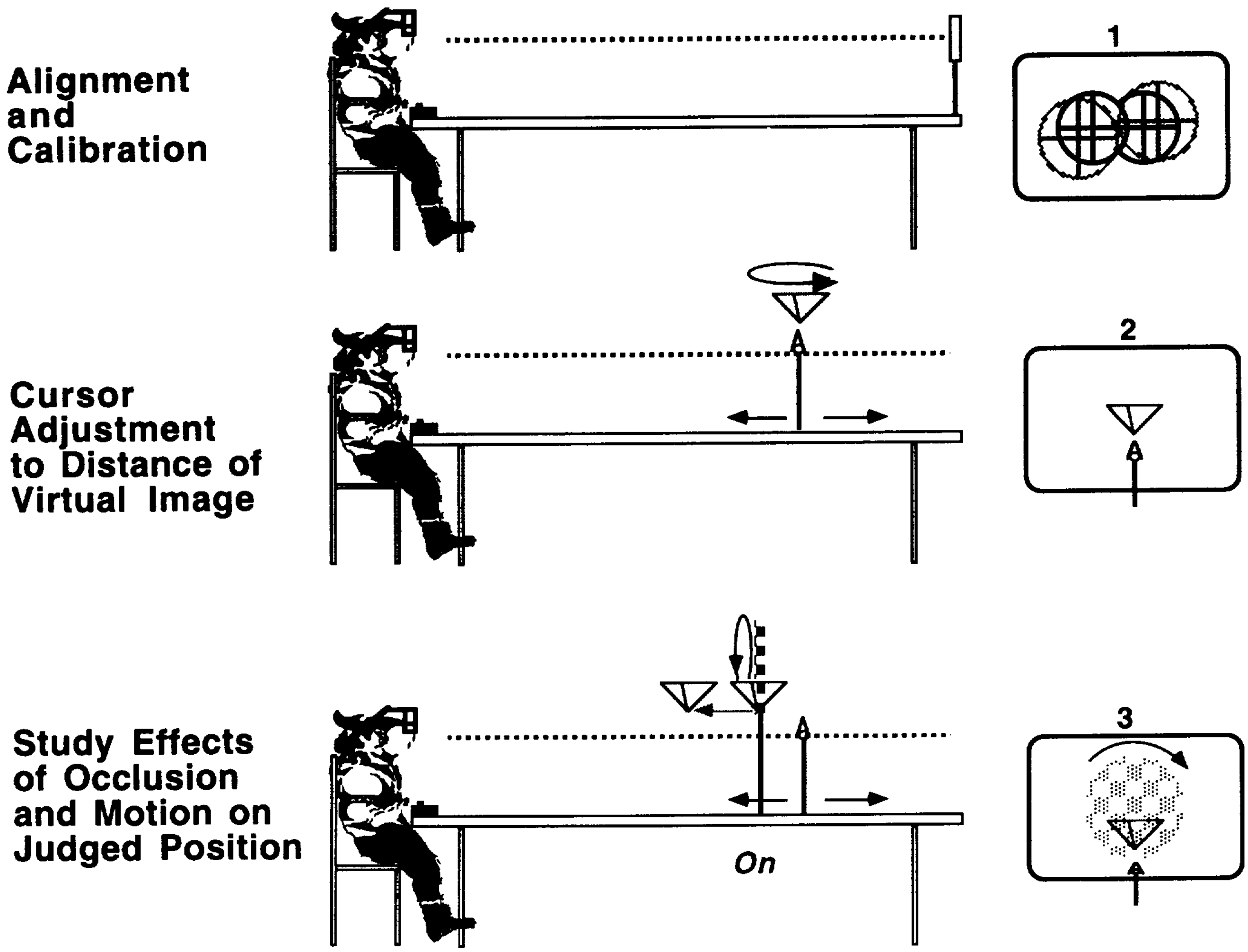

Figure 7 - an experimental scheme for examining the effects of the judged distance to computer-generated rotating virtual objects after they have been superimposed on rotating physical surfaces. After adjustment of the display parameters to correctly display visual direction for both the left and right eyes independently (top panel), the depth of a stereoscopically presented virtual object can be pointed out with a physical cursor to an accuracy of several millimeters (middle panel). Interposition of a physical surface at the judged depth of the virtual object causes the virtual object to appear to move closer to the observer (lower panel) (see Ref. 10 for experimental details).

Displays such as the one illustrated in Fig. 8, used to plan orbital maneuvers, do not depend upon photo realistic naturalness, but fluent, low-order control of animated graphical icons displaying constraints, status, and the future conditions of objects. In this case, a carefully controlled presentation of the counter-intuitive aspects of orbital mechanics was the key innovation, not making the astronauts feel that they were in orbit (Ref. 11).

This display of the counter-intuitive and nonlinear aspects of orbital maneuvering has provided a basis for the design and testing of a special format that allows *in situ* design of minimum-fuel, multi-burn maneuvers in a simulated multi-spacecraft planning environment. By focusing on the symbolic, geometric, and dynamic enhancements to synthetic environments, it provides examples of features that may be usefully incorporated into actual orbital display systems.

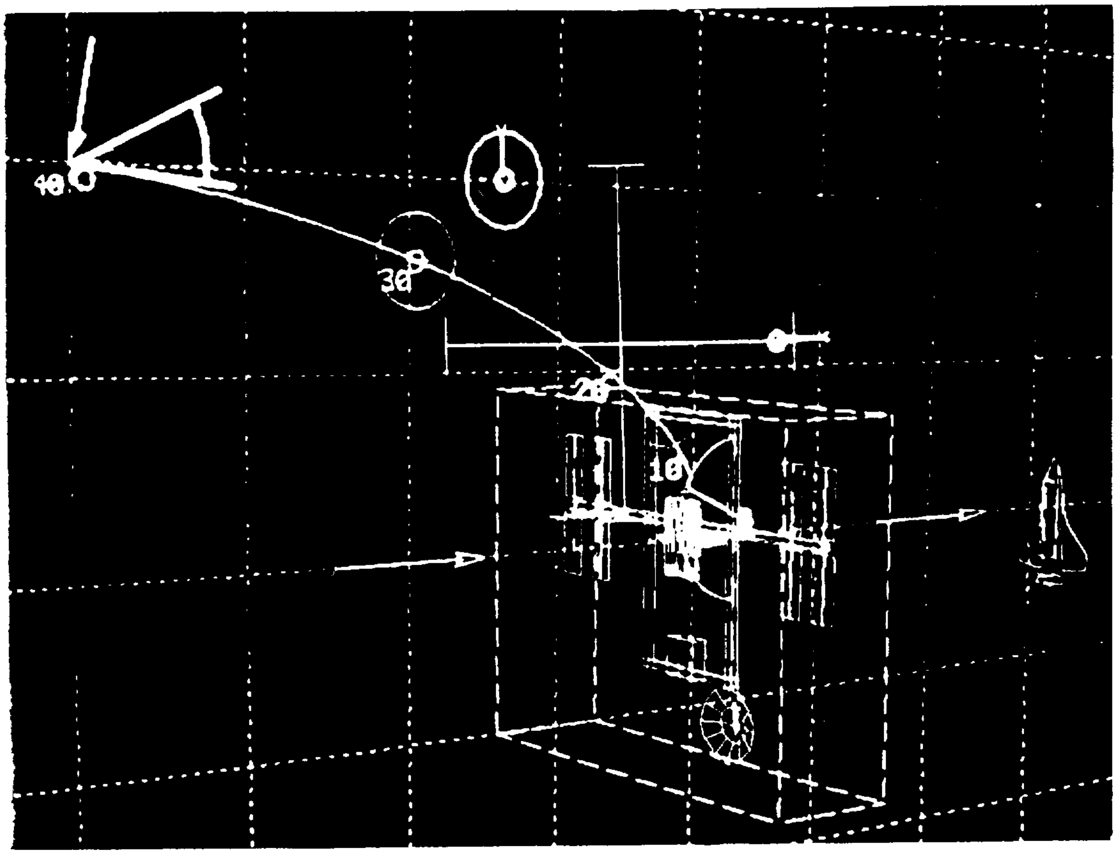

Figure 8 - A display for planning short duration orbital maneuvers subject to realistic maneuvering constraints.

The difficulty in informal planning of orbital missions arises from 1) the higher-order, nonlinear control dynamics of orbital maneuvering, 2) the counter-intuitive character of relative orbital motion, and 3) the frequent absence of stable reference points. The difficulties these characteristics pose for missions conforming to operational constraints on relative velocity, thruster plumes, and collision risk may be substantially overcome by visualizing the orbital trajectories and constraints in a pictorial, perspective display.

Though the visualization used in the display most directly assists planning by providing visual feedback to aid visualization of the trajectories and constraints, its most significant novel design features include 1) *an inverse dynamics algorithm* that reduces the order of control while also removing control nonlinearities expected from the operator, and 2) a trajectory planning mode that creates, through a geometric spread-sheet, the *illusion of an inertially stable environment.* Consequently, the display is not just a "pretty picture," illustrating that computer graphics can be used to model orbital motion. It is rather a spatial instrument for interacting with orbital dynamics and now is in use in a number of laboratories around the world.

This synthetic planning environmental provides the user with control of relevant static and dynamic properties of mid-course thrusts during small orbital changes allowing independent solutions to the normally coupled problems of orbital maneuvering.

This display illustrates how a synthetic environment may be defined so as to couple human problem solving abilities with the computer's computational capacities so as to enable interactive optimization of complex evaluation functions. Furthermore, it illustrates that the synthetic environments defined to enhance man-machine communication can benefit from informative symbolic, geometric, and dynamic enhancements.

As a display of error, i.e., constraint violation, this maneuvering display is distinctly non-McLuhan. This media is not the message. The focus of interest is the display and control of error, not visual impact. Thus, the paramount consideration in the design of a virtual environment as an environmental instrument is the information to be communicated and the error to be controlled.

REFERENCES

1. Ellis, Stephen R., "Nature and Origin of Virtual Environments: A Bibliographical Essay," *Computer Systems in Engineering*, Vol. 2, No. 4, 1991, pp. 321-347.

2. Brody, Adam R., Jacoby, Richard and Ellis, Stephen R., "Extravehicular Activity Self Rescue Using a Handheld Thruster," *Journal of Spacecraft and Rockets*, Vol. 29, No. 6, pp. 842-848.

3. Homan, D. J., "Virtual Reality and the Hubble Telescope," Space Programs and Technology Conference, Huntsville, AL, Sept. 27-29, 1994, AIAA Paper 94-4558.

4. Ellis, Stephen R., Kaiser, Mary K. and Grunwald, Arthur J., *Pictorial Communication in Virtual and Real Environments*, second ed., Taylor and Francis, London, 1993, pp. 28-39.

5. Ellis, Stephen R., McGreevy, Michael W., Hitchcock, Robert, "Perspective Traffic Display Format and Airline Pilot Traffic Avoidance," *Human Factors*, Vol. 29, 1987, pp. 371-382.

6. McGreevy, Michael W. and Ellis, Stephen R., *Format and Basic Geometry of a Perspective Display of Air Traffic for the Cockpit*, NASA TM-86680, Ames Research Center, Moffett Field, CA, 1991.

7. Comeau, C. P. and Brian, J. S., "Headsight Television System Provides Remote Surveillance," *Electronics*, Nov. 10, 1961, pp. 86-90.

8. Sutherland, I. E., "The Ultimate Display," *International Federation of Information Processing*, Vol. 2, 1965, p. 506.

9. Adelstein, Bernard D. and Ellis, Stephen R., "Effect of Head-Slaved Visual Image Roll on Spatial Situation Awareness," *Proceedings 37th Annual Meeting of the Human Factors and Ergonomics Society*, Santa Monica, CA, 1993, pp. 1350-1354.

10. Ellis, Stephen R., Bucher, Urs J. and Menges, Brian M., "The Relationship of Binocular Convergence and Errors in Judged Distance to Virtual Objects," *Proceedings of the International Federation of Automatic Control*, June 27-29, 1995, Boston, MA.

11. Grunwald, Arthur J. and Ellis, Stephen R., "A Visual Display Aid for Orbital Maneuvering: Design Considerations, *AIAA Journal of Guidance and Control*, Vol. 16, No. 1, pp. 139-144.