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NATURE AND ORIGINS OF VIRTUAL ENVIRONMENTS: A BIBLIOGRAPHICAL ESSAY

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Abstract—Virtual environments presented via head-mounted, computer-driven displays provide a new media for communication. They may be analyzed by considering: (1) what may be meant by an environment; (2) what is meant by the process of virtualization; and (3) some aspects of human performance that constrain environmental design. Their origins are traced from previous work in vehicle simulation and multimedia research. Pointers are provided to key technical references, in the dispersed, archival literature, that are relevant to the development and evaluation of virtual-environment interface systems.

1. COMMUNICATION AND ENVIRONMENTS

1.1. *Virtual environments are media*

Virtual environments created through computer graphics are communications media.[1] Like other media, they have both physical and abstract components. Paper, for example, is a medium for communication. The paper is itself one possible physical embodiment of the abstraction of a two-dimensional surface onto which marks may be made.† The corresponding abstraction for head-coupled, virtual image, stereoscopic displays that synthesize a coordinated sensory experience is an environment. These so called "virtual reality" media have only recently caught the international public's imagination,[3–6] but they arise from continuous development in several technical and nontechnical areas during the past 25 years.

1.2. *Optimal design*

A well designed computer interface affords the user an efficient and effortless flow of information to and from the device with which he interacts. When users are given sufficient control over the pattern of this interaction, they themselves can evolve efficient interaction strategies that match the coding of their communications to the characteristics of their communication channel.[7–10] But successful interface design should strive to reduce this adaptation period by analysis of the user's task and performance limitations. This analysis requires understanding of the operative design metaphor for the interface in question.

The dominant interaction metaphor for the computer interface changed in the 1980s. Modern graphical interfaces, like those first developed at Xerox PARC[11] and used for the Apple Macintosh (Fig. 1), have transformed the "conversational" interaction from one in which users "talked" to their computers to one which they "acted out" their commands in a "desk-top" display. This so called desk-top metaphor provides the users with an illusion of an environment in which they enact wishes by manipulating symbols on a computer screen.

1.3. *Extensions of the desk-top metaphor*

Virtual environment displays represent three-dimensional generalization of the two-dimensional "desk-top" metaphor.‡ These synthetic environments may be experienced either from egocentric or exocentric viewpoints. That is to say, the users may appear to actually be in the environment or see themselves represented as a "You are here" symbol[14] which they can control.

The objects in this synthetic universe, as well as the space itself within which they exist, may be programmed to have arbitrary properties. However, the successful extension of the desk-top metaphor to a full "environment" requires an understanding of the necessary limits to programmer creativity in order to insure that the environment is comprehensible and usable. These limits derive from human experience in real environments and illustrate a major connection between work in telerobotics and virtual environments. For reasons of simulation fidelity, previous telerobotic and aircraft simulations, which have many of the aspects of virtual environments, have had to explicitly take into account real-world kinematic and

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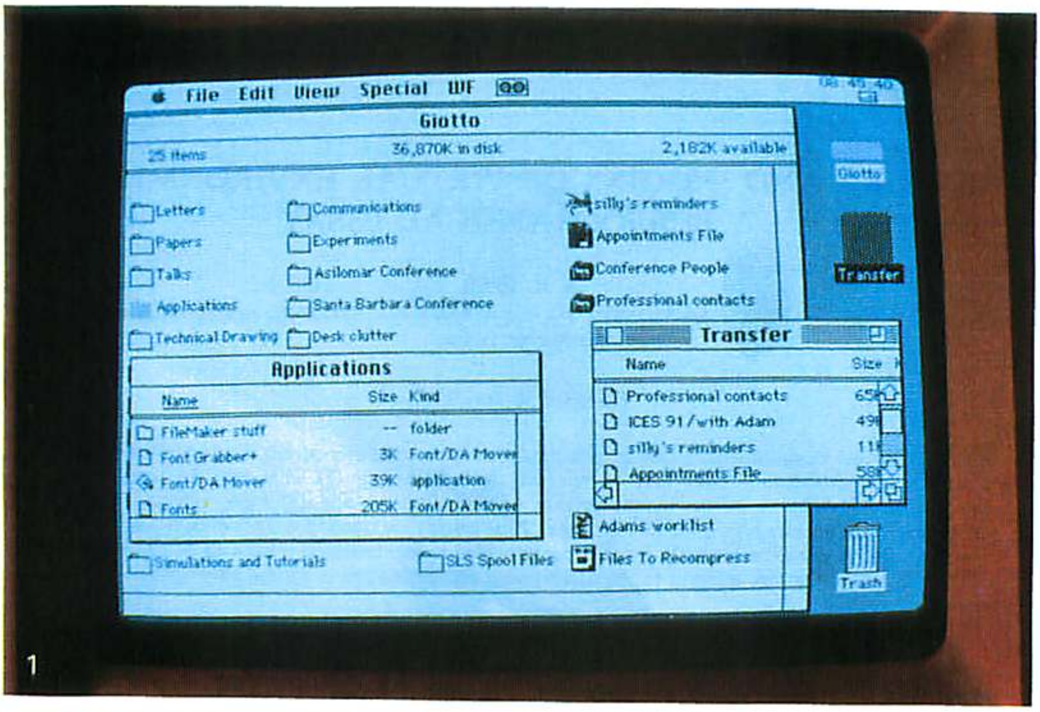
† As described by James Hollan at the Panel on Virtual Reality, Western Communications Forum Panel 1991, Phoenix, Arizona, some new computer interfaces may resemble handwriting-recognizing magic slates on which users write commands with a stylus. See Ref. 2.

‡ Higher dimensional displays have also been described. See Ref. 12 and 13 for alternative approaches.



Applications

Name	Size	Kind
FileMaker stuff	--	folder
Font Grabber+	3K	Font/DA Mover
Font/DA Mover	39K	application
Fonts	205K	Font/DA Mover

Fig. 1. Macintosh® screen display illustrating graphical icons with which the user interacts to control the computer's operating system. This mode of acting out commands was initially developed at Xerox PARC.

dynamic constraints in ways now usefully studied by the designers of totally synthetic environments.[15-19]

1.4. *Environments*

Successful synthesis of an environment requires some analysis of the parts that make up the environment. The theatre of human activity is an *environment* and may be considered to have three parts: a *content*, a *geometry*, and *dynamics*.[20]

1.4.1. *Content.* The *objects and actors* in the environment are its content. These objects may be described by *state vectors* which identify their position, orientation, velocity, and acceleration in the environmental space, as well as other distinguishing characteristics such as their color, texture, and energy. The state vector is thus a description of the *properties* of the objects. The subset of all the terms of the state vector which is common to every actor and object of the content may be called the *position vector*. Though the *actors* in an environment may, for some interactions, be considered objects, they are distinct from objects in that in addition to characteristics they have *capacities* to initiate interactions with other objects. The basis of these initiated interactions is the storage of energy or information within the actors, and their ability to control the release of this stored information or energy after a period of time. The *self* is a distinct actor in the environment which provides a *point of view* from which the environment may be constructed. All parts of the environment that are exterior to the self may be considered the field of action. As an example, the balls on a billiard table may be considered the content of the billiard table environment and the cue ball combined with the pool player maybe considered the "self".

1.4.2. *Geometry.* The geometry is a description of an environmental field of action. It has *dimensionality*, *metrics* and *extent*. The dimensionality refers to the number of independent descriptive terms needed to specify the position vector for every element of the environment. The metrics are systems of rules that may be applied to the position vector to establish an ordering of the contents and to establish the concept of geodesic or straight lines in the environmental space. The extent of the environment refers to the range of possible values for the elements of the position vector. The environmental space or field of action may be defined as the Cartesian product of all the elements of the position vector over their possible ranges. An environmental trajectory is a time-history of an object through the environmental space. Since kinematic constraints may preclude an object from traversing the space along some paths; these constraints are also part of the environment's geometric description.

1.4.3. *Dynamics.* The dynamics of an environment are the *rules of interaction* among its contents describing their behavior as they exchange energy or information. Typical examples of specific dynamical rules may be found in the differential equations of Newtonian dynamics describing the response of billiard balls to impacts initiated by the cue ball. For other

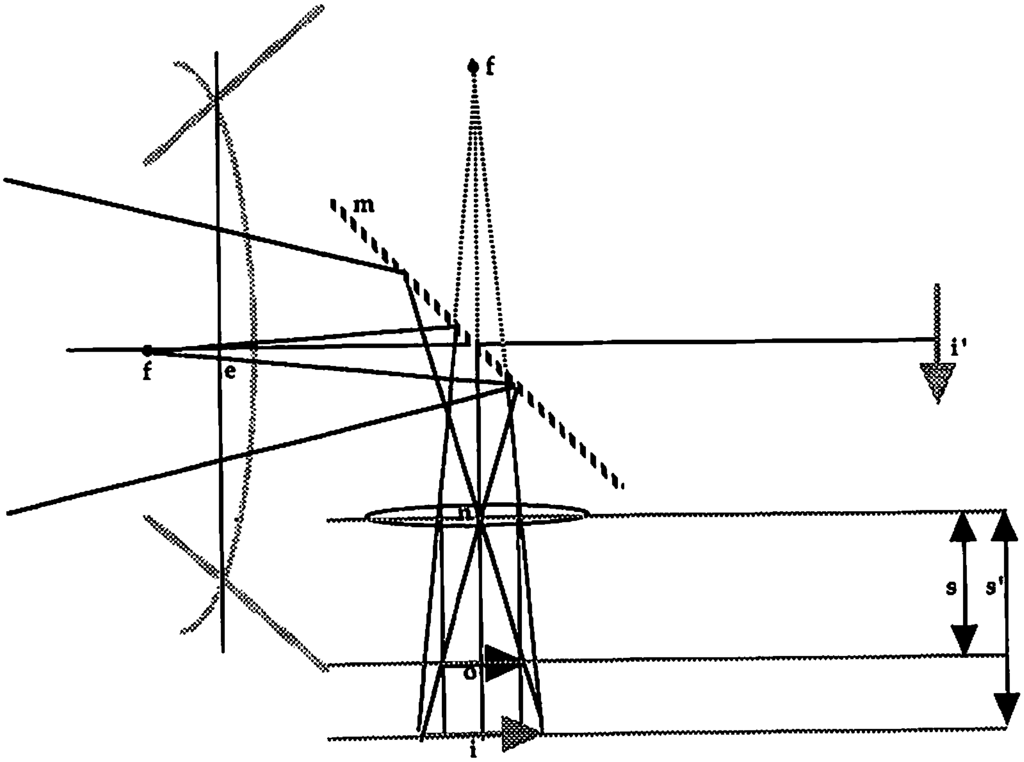


Fig. 2. Virtual image created by a simple lens with focal length *f* placed at *n* and viewed from *e* through a half-silvered mirror at *m* appears to be straight ahead of the viewer at *i'*. The visual direction and accommodation required to see the virtual image clearly are quite different than what would be needed to see the real object at *o*. An optical arrangement similar to this would be needed to superimpose synthetic computer imagery on a view of a real scene as in at heads up display.

environments, theses rules may also take the form of grammatical rules or even of look-up tables. For example, a syntactically correct command typed at a computer terminal can cause execution of a program with specific parameters. In this case the information in the command plays the role of the energy, and the resulting rate of change in the logical state of the device, plays the role of acceleration.†

1.5. *Sense of physical reality*

Our sense of physical reality is a construction from the symbolic, geometric, and dynamic information directly presented to our senses. It is noteworthy that many of the aspects of physical reality are only presented in incomplete, noisy form. We, for example, generally see only part of whole objects, yet through *a priori* knowledge that we bring to perceptual analysis, we know them to exist in their entirety.[21 23] Similarly, our goal seeking behavior appears to filter noise by benefiting from internal dynamical models of the objects we may track or control.[24,25] Accurate perception consequently involves considerable *a priori* knowledge about the possible structure of the world. This knowledge is under constant recalibration based on error feedback. The role of error feedback has been classically mathematically modeled during tracking behavior[26 28] and notably demonstrated in the behavioral plasticity of visual-motor coordination[29 31] and in vestibular reflexes.[32 34]

Thus, a large part of our sense of physical reality is a consequence of internal processing rather than being something that is developed only from the immediate sensory information we receive. Our sensory and cognitive interpretive systems are predisposed to process incoming information in ways that normally result in a correct interpretation of the external environment, and in some cases they may be said to actually "resonate" with specific patterns of input that are uniquely informative about our environment.[35 38]

These same constructive processes are triggered by the displays used to present virtual environments. However, in these cases the information is mediated through the display technology. The illusion of a enveloping environment depends on the extent to which all of these constructive processes are triggered. Accordingly, virtual environments can come in differ-

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† This analogy suggests the possibility of developing an *informational mechanics* in which some measure of motion through the states of an information processing device may be related to the information content of the incoming messages. In such mechanics, the proportionality constant relating the change in motion to the message content might be considered the *informational mass* of the program.

Fig. 3. See-through, head-mounted, virtual image, stereoscopic display that allows the user to interact with virtual objects synthesized by computer graphics which are superimposed in his field of vision.[39] The user's hand position is tracked electromagnetically and its shape is measured by the VPL DataGlove®. (Photograph courtesy of Michitaka Hirose.)

ent stages of completeness, which may be usefully distinguished.

2. VIRTUALIZATION

2.1. *Definition of virtualization*

Virtualization may be defined as *the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists*. A classical example would be that of a virtual image as defined in geometrical optics. A viewer of such an image sees the rays emanating from it as if they originated from a point that could be computed by the basic lens law rather that from their actual location (Figs 2 and 3).

Virtualization, however, extends beyond the objects to the spaces in which they themselves may move. Consequently, a more detailed discussion of what it means to *virtualize* an environment is required.

2.2. *Levels of virtualization*

Three levels of virtualization may be distinguished: virtual space, virtual image, and virtual environments.

2.2.1. *Virtual space*. The first form, construction of a virtual space, refers to the process by which a viewer perceives a three-dimensional layout of objects in space when viewing a flat surface presenting the pictorial cues to space, that is, perspective, shading, occlusion, and texture gradients. This process, which is akin to map interpretation, is the most abstract of the three. It is abstract because many of the physiological reflexes associated with the experience of a real three-dimensional environment are either missing or inappropriate for the information on a flat picture. The basis of the reconstruction of virtual space must be the optic array, the patterned collection of relative lines of sight to significant features in the image, that is, contours, vertices, lines, and textured regions. Since scaling does not affect the relative position of the features of the optic array, perceived size or scale is not intrinsically defined in a virtual space.

2.2.2. *Virtual image*. The second form of virtualization is the perception of a virtual image. In conformance with the use of this term in geometric optics, it is the perception of an object in depth in which accommodative,† vergence,‡ and (optionally) stereoscopic disparity§ cues are present, though not necessarily consistent.[40] Since, virtual images can incorporate stereoscopic and vergence cues, the actual perceptual scaling of the constructed space is not arbitrary but, somewhat surprisingly, not simply related to viewing geometry.[41–43]

2.2.3. *Virtual environment*. The final form is the virtualization of an environment. In this case the key added sources of information are observer-slaved motion parallax, depth-of-focus variation, and wide field-of-view without a prominent frame. If properly implemented, these additional features can be consistently synthesized to provide stimulation of major physiological reflexes such as accommodative vergence,‖ vergence accommodation,¶ the optokinetic reflex,†† and the vestibular-ocular reflex.‡‡[44–45] These features when embellished by synthesized sound sources[46–50] can substantially contribute to an illusion of telepresence, that is, actually being present in the synthetic environment.

The fact that actors in virtual environments interact with objects and the environment by hand, head, and eye movements, tightly restricts the subjective scaling of the space so that all system gains must be

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† Focusing required of the eye to make a sharp image on the retina.

‡ Convergence or divergence of the eyes to produce an apparently single image.

§ The binocular disparity to a point in space is the difference of the binocular parallax of that point measured from both eyes.

‖ Reflexive changes in the convergence of the eyes triggered by changes in the required focus.

¶ Reflexive changes in the focusing of the eye triggered by change in convergence.

†† Reflexive tracking eye movements triggered by movement of objects subtending large visual angles.

‡‡ Tracking eye movements triggered by vestibular stimulation normally associated with head or body movement.

carefully set. Mismatch in the gains or position measurement offsets will degrade performance by introducing unnatural visual-motor and visual-vestibular correlations. In the absence of significant time lags, humans can adapt to these unnatural correlations. However, time lags do interfere with complete visual-motor adaptation,[31,32] and when present in the imaging system can cause motion sickness.[51]

2.3. *Environmental viewpoints and controlled elements*

Virtual spaces, images or environments may be experienced from two kinds of viewpoints: egocentric viewpoints, in which the sensory environment is constructed from the viewpoint actually assumed by the user, and exocentric viewpoints in which the environment is viewed from a position other than that where the user is represented to be. In this case, the user can literally see a representation of himself. This distinction in frames of reference results in a fundamental difference in movements a user must make to track a visually referenced target. Egocentric viewpoints require compensatory tracking, and exocentric viewpoints require pursuit tracking. This distinction also corresponds to the difference between inside-out and outside-in frames of reference in the aircraft simulation literature. The substantial literature on relative human tracking performance in these alternative reference frames, and the general literature on human manual performance, may be useful in the design of synthetic environments.[52–53]

3. ORIGINS OF VIRTUAL ENVIRONMENTS

3.1. *Early visionaries*

The intuitive appeal that virtual environment technology obviously has is probably rooted in the human fascination with vicarious experiences in imagined environments. In this respect, virtual environments may be thought of as originating with the earliest human cave art,[54] though Lewis Carroll's *Through the Looking-Glass* certainly is a more modern example of this fascination.

Fascination with alternative, synthetic realities has been continued in more contemporary literature. Aldous Huxley's "feelies" in *Brave New World* were certainly a kind of virtual environment, a cinema with sensory experience extended beyond sight and sound. A similar fascination must account for the popularity of microcomputer role playing adventure games such as *Wizzardry*. Motion pictures, and especially stereoscopic movies, of course, also provide examples of noninteractive spaces.[55]

The contemporary interest in imagined environments has been particularly stimulated by the advent of sophisticated, relatively inexpensive, interactive techniques allowing the inhabitants of these environments to move about and manually interact with computer graphics objects in three-dimensional space. This kind of environment was envisioned in the science fiction plots of the movie *TRON* and William Gibson's 1985 *Neuromancer*, yet the first actual synthesis of such a system using a head-mounted stereo display was made possible much earlier in the middle 1960s by Ivan Sutherland who developed special-purpose fast graphics hardware.[56,57]

Another early synthesis of a synthetic, interactive environment was implemented by Myron Krueger[58–60] in the 1970s. Unlike the device developed for Sutherland, Krueger's environment was projected onto a wall-sized screen. In Krueger's VIDEOPLACE, the user's image appears in a two-dimensional graphic video world created by a computer. The VIDEOPLACE computer analyzed video images to deter-

Fig. 4. View through the cockpit of a 727 simulator at the Ames Research Center which is used for human factors research. A simulated night flying environment is visible out the forward cockpit window. (Photograph courtesy of NASA.)

Fig. 5. This head-mounted, stereo, virtual environment display system at the Ames Research Center Advanced Display and Spatial Perception Laboratory is being used to control a remote PUMA robot in the Ames Robotics Laboratory. The simulation update rate varies from 12 to 30 Hz, depending on the complexity of the graphics. A local kinematic simulation of the remote work site aids the operator in planning complex movements and visualizing kinematic and operational constraints on the motion of the end effector. (Photography courtesy of NASA.)

mine when an object was touched by an inhabitant, and it could then generate a graphic or auditory response. One advantage of this kind of environment is that the remote video-based position measurement does not encumber the user with position sensors.

3.2. *Vehicle simulation and three-dimensional cartography*

Probably the most important source of virtual environment technology comes from previous work in fields associated with the development of realistic vehicle simulators, primarily for aircraft (see Refs 61 and 62; and Fig. 4), but also automobiles[63] and ships.[64,65] The inherent difficulties in controlling the actual vehicles often require that operators be highly trained. Since acquiring this training on the vehicles themselves could be dangerous or expensive, simulation systems synthesize the content, geometry, and

Fig. 6. As in all current relatively inexpensive, head-mounted virtual environment viewing systems, the view that the operator actually sees through the wide field (lower inset shows a part of the user's actual field of view) view finder is significantly lower resolution than that typically seen on the graphics monitors (background matched in magnification). The horizontal pixel resolution through view finder is about 22 arcmin/pixel, vertical resolution is 24 arcmin/line. Approximately 2 arcmin/pixel are required to present resolution at the center of the visual field comparable to that seen on a standard Macintosh monochrome display viewed at 57 cm. (Photograph courtesy of NASA.)

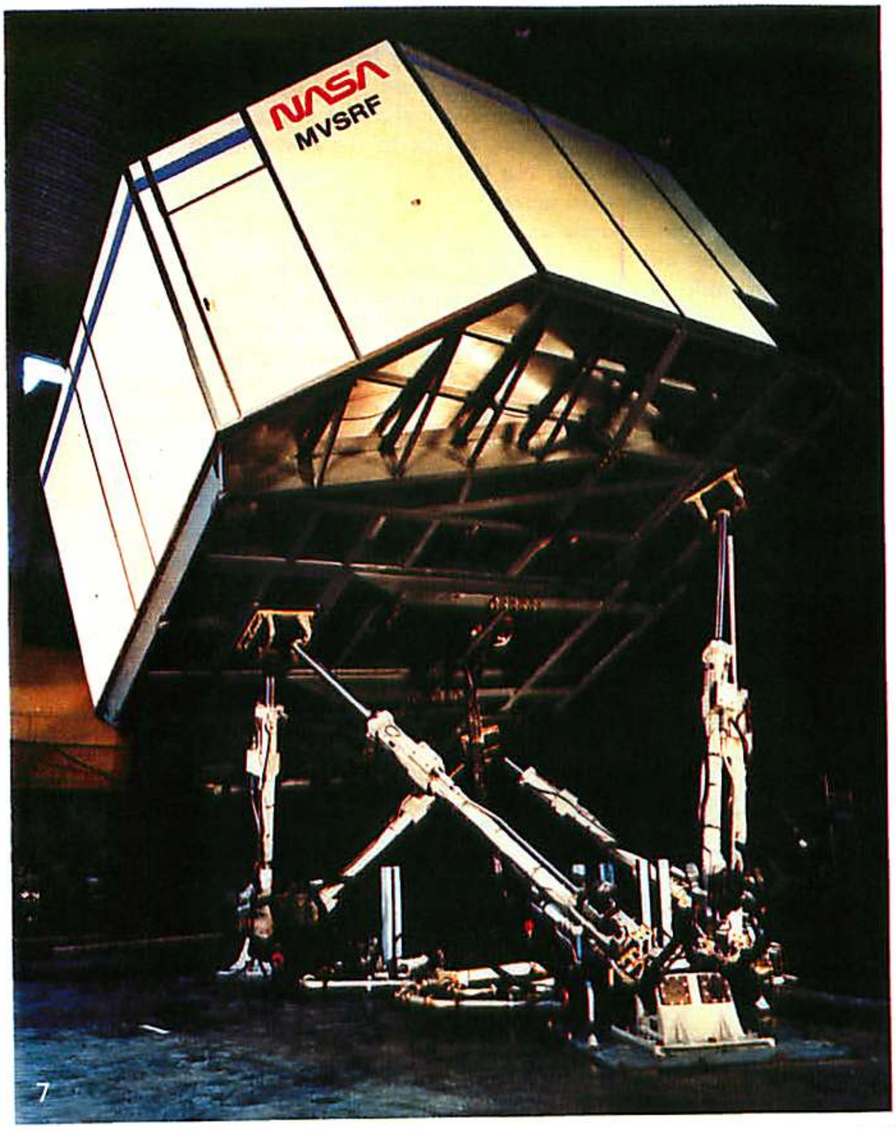

Fig. 7. Moving base simulator of the Aerospace Human Factors Division of Ames Research Center pitched so as to simulate an acceleration. (Photograph courtesy of NASA.)

dynamics of the control environment for training and for testing of new technology and procedures.

These systems have usually cost millions of dollars and have recently involved helmet-mounted displays to recreate part of the environment.[66–69] Declining costs have now brought the cost of a virtual environment display down to that of an expensive workstation and made possible "personal simulators" for everyday use (see Refs 70 and 71; and Figs 5 and 6).

The simulator's interactive visual displays are made by computer graphics hardware and algorithms. Development of special-purpose hardware, such as matrix multiplication devices, was an essential step that enabled generation of real-time, that is, greater than 20 Hz, interactive three-dimensional graphics.[56,57,72] A recent example is the "geometry engine" in Silicon Graphics IRIS workstations.[73,74] It enhances processing of the viewing transformation. These "graphics engines" can project hundreds of thousands of Gouraud shaded polygons per second.[75] Though this number may seem large, rendering of naturalistic objects and surfaces can require from 10,000 to 500,000 polygons. Software techniques are also important for improved three-dimensional graphics performance. "Oct-tree" data structures, for example, have been shown to dramatically improve processing speed for inherently volumetric structures.[76,77]

Since vehicle simulation may involve moving-base simulators, programming the appropriate correlation between visual and vestibular simulation is crucial for a complete simulation of an environment (Fig. 7). Moreover, failure to match these two stimuli correctly can lead to motion sickness.[78] Paradoxically, however, since the effective travel of most moving base simulators is limited, designers must learn how to use subthreshold visual-vestibular mismatches to produce illusions of greater freedom of movement. These allowable mismatches are built into so-called "washout" models[16,79] and are key elements for creating illusions of extended movement. For example, a slowly implemented pitch-up of a simulator can be used to help create an illusion of forward acceleration. Understanding the tolerable dynamic limits of visual-vestibular miscorrelation will be an important design consideration for wide field-of-view head-mounted displays.

The use of informative distortion is also well established in cartography[80] and is used to help create a convincing three-dimensional environment for simulated vehicles. Cartographic distortion is also obvious in global maps which must warp a spherical surface into a plane[81,82] and three-dimensional maps, which often use significant vertical scale exaggeration (6–20×) to clearly present topographic features. Explicit informative geometric distortion is sometimes incorporated into maps and cartograms presenting geographically indexed statistical data,[81–87] but the extent to which such informative distortion may be incorporated into simulated environments is constrained by the user's movement-related physiological reflexes. If the viewer is constrained to actually be *in* the environment, deviations from a natural environmental space can cause disorientation and motion sickness.[51,88] For this reason, virtual space or virtual image formats are more suitable when successful communication of the spatial information may be achieved through spatial distortions (Fig. 8). However, even in these formats the content of the environment may have to be enhanced by aids such as graticules to help the user discount unwanted aspects of the geometric distortion.[89–91]

In some environmental simulations the environment itself is the object of interest. Truly remarkable animations have been synthesized from image sequences taken by NASA spacecraft which mapped various planetary surfaces. When electronically combined with surface altitude data, the surface photography can be used to synthesize flights over the surface through positions never reached by the space-

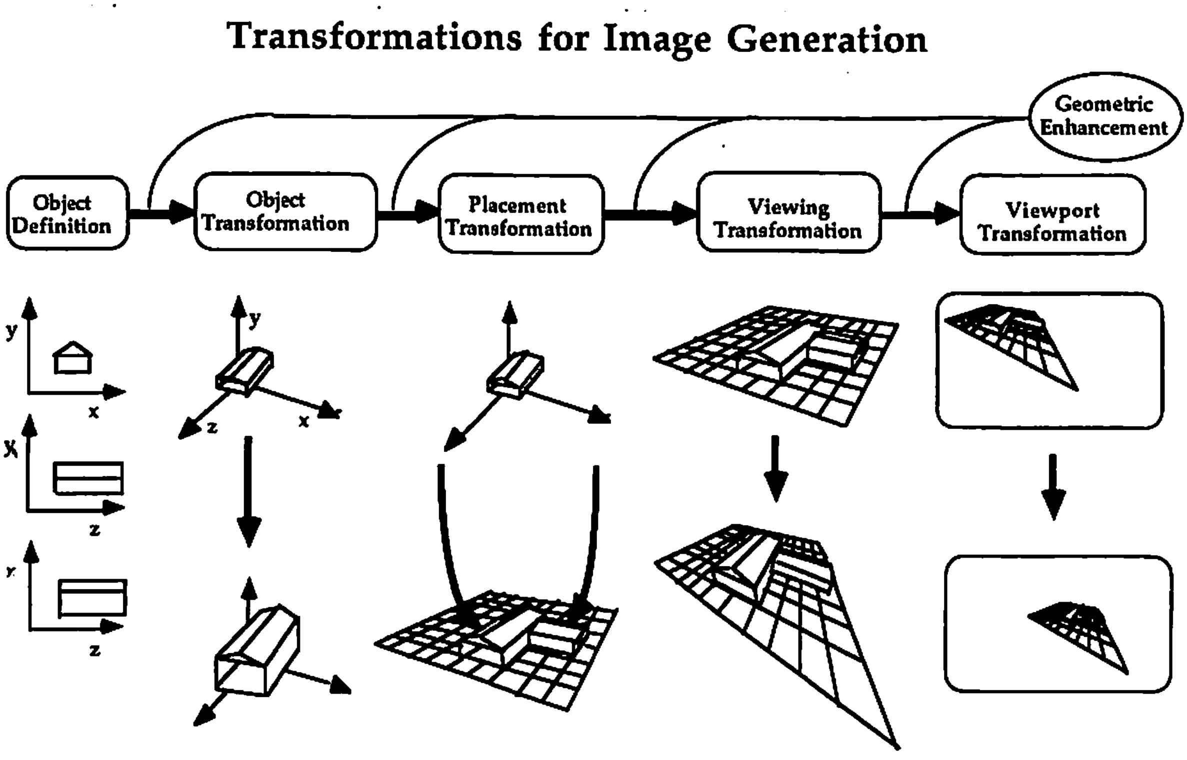

Fig. 8. Process of representing a graphic object in virtual space allows a number of different opportunities to introduce informative geometric distortions or enhancements. These may either be a modification of the transforming matrix during the process of object definition or they may be modifications of an element of a model. These modifications may take place (1) in an object relative coordinate system used to define the object's shape, or (2) in an affine or even curvilinear object shape transformation, or (3) during the placement transformation that positions the transformed object in world coordinates, or (4) in the viewing transformation or (5) in the final viewport transformation. The perceptual consequences of informative distortions are different depending on where they are introduced. For example, object transformations will not impair perceived positional stability of objects displayed in a head-mounted format, whereas changes of the viewing transformation such as magnification will.

Fig. 9. When high-performance computer display technology can be matched to equally high resolution helmet display technology, planetary scientists will be able to use these systems to visualize remote environments such as the surface of Mars to plan exploration and to analyze planetary surface data. (Photograph courtesy of NASA.)

craft's camera.[92] Recent developments have made possible the use of these synthetic visualizations of planetary and Earth surfaces for interactive exploration and they promise to provide planetary scientists with the new capability of "virtual planetary exploration".[93,94] (Fig. 9).

3.3. *Physical and logical simulation*

Visualization of planetary surfaces suggests the possibility that not only the substance of the surface may be modeled but also its dynamic characteristics. Dynamic simulations for virtual environments may be developed from ordinary high-level programming languages like Pascal or C, but this usually requires considerable time for development. Interesting alternatives for this kind of simulation have been provided by simulation and modeling languages such as SLAM II, with a graphical display interface, TESS.[95] These very high languages provide tools for defining and implementing continuous or discrete dynamic models. They can facilitate construction of precise systems models.[96]

Another alternative made possible by graphical interfaces to computers is a simulation development environment in which the simulation is created through manipulation of icons representing its separate elements, such as integrators, delays, or filters, so as to connect them into a functioning *virtual machine*. A microcomputer program called "Pinball Construction Set" published in 1982 by Bill Budge is a widely distributed early example of this kind of simulation system. It allowed the user to create custom simulated pinball machines on the computer screen simply by moving icons from a tool kit into an "active region" of the display where they would become animated. A more educational, and detailed example of this kind of simulator was written as educational software by Warren Robinett. This program, called "Rocky's Boots",[97] allows users to connect icons representing logic circuits that are animated at a slow rate so the user may watch their detailed functioning. More detailed versions of this type of simulation have now been incorporated into graphical interfaces to simulation and modeling languages and are available through widely distributed systems such as the interface builder distributed with NeXt® computers.

The dynamical properties of virtual spaces and environments may also be linked to physical simulations. Prominent, noninteractive examples of this technique are James Blinn's physical animations in the video physics courses, "The Mechanical Universe" and "Beyond the Mechanical Universe."[98,99] These physically correct animations are particularly useful in providing students with subjective insights into dynamic three-dimensional phenomena such as magnetic fields. Similar educational animated visualizations have been used for courses on visual perception[100] and computer-aided design.[101] Physical simulation is more instructive, however, if it is interactive and interactive virtual spaces have been constructed which allow users to interact with nontrivial physical simulations by manipulating synthetic objects whose behavior is governed by realistic dynamics (see Refs 102 and 103; also see Figs 10 and 11).

Some unusual natural environments are difficult to work in because their inherent dynamics are unfamiliar and may be nonlinear. The immediate environment around an orbiting spacecraft is an example. When expressed in a spacecraft-relative frame of reference known as local-vertical-local-horizontal, the consequences of maneuvering thrusts becomes markedly counter-intuitive and nonlinear.[106] Consequently, a visualization tool designed to allow

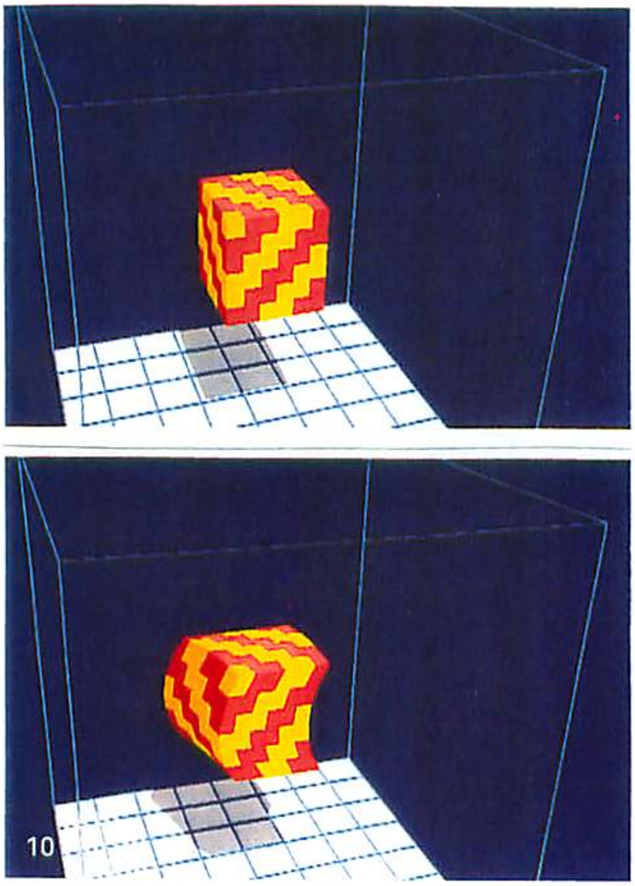

Fig. 10. Nonrigid cube is dynamically simulated to deform when a force is applied. Though computationally expensive, this kind of dynamic simulation will markedly increase the apparent realism of virtual environments. (Photograph courtesy of Andrew Witkin.)

manual planning of maneuvers in this environment has taken account of these difficulties.[107–109] This display system most directly assists planning by providing visual feedback of the consequences of the proposed plans. Its significant features enabling interactive optimization of orbital maneuvers include an "inverse dynamics" algorithm that removes control nonlinearities. Through a "geometric spread-sheet", the display creates a synthetic environment that provides the user control of thruster burns which allows *independent* solutions to otherwise coupled problems of orbital maneuvering (Figs 12 and 13.)

3.4. *Scientific and medical visualization*

Visualizing physical phenomena may be accomplished not only by constructing simulations of the phenomena but also by animating graphs and plots of the physical parameters themselves.[98,99] For example, multiple time functions of force and torque and the joints of a manipulator or limb while it is being used for a test movement (see, for example, Ref. 110).

One application for which a virtual space display has already been demonstrated in a commercial product has been in visualization of volumetric medical data.[77] These images are typically constructed from a series of two-dimensional slices of CAT, PET, or MRI images in order to allow doctors to visualize normal or abnormal anatomical structures in three dimensions. Because the different tissue types may be identified digitally, the doctors may perform an "electronic dissection" and selectively remove particular tissues. In this way truly remarkable skeletal images may be created which currently aid orthopedic and cranio-facial surgeons to plan operations (Figs 14 and 15). These volumetric data bases are also useful for shaping custom-machined prosthetic bone implants and for directing precision robotic boring devices for precise fit between implants and surrounding bone.[111] Though these static data bases have not yet been presented to doctors as full virtual environments, existing technology is adequate to develop improved virtual space techniques for interacting with them and may be able to enhance the usability of the existing displays. Related scene-generation technology can already render detailed images of this sort based on architectural drawings and can allow prospective clients to visualize walk-throughs of buildings that have not yet been constructed.[112,113]

Fig. 11. Virtual environment technology may assist visualization of the results of aerodynamic simulations. Here a DataGlove is used to control the position of a "virtual" source of smoke in a wind-tunnel simulation so the operator can visualize the local pattern of air flow. In this application the operator uses a viewing device incorporating TV monitors[104] to present a stereo view of the smoke trail around the test model also shown in the desk-top display on the table.[105] (Photograph courtesy of NASA.)

3.5. *Teleoperation and telerobotics and manipulative simulation*

The second major technical influence on the development of virtual environment technology is research on teleoperation and telerobotic simulation.[19,114,115] Indeed, virtual environments have existed before the name itself as telerobotic and teleoperations simulations. The display technology, however, in these cases was usually panel-mounted rather than head-mounted (but see Ref. 116). A key difficulty was lack of a convenient and cheap head tracker. The current popular, electromagnetic, six-degree-of-freedom position tracker developed by Polhemus Navigation,[117] and also see Ref. 118 and 119, consequently, was a key technological advance. In other techniques for tracking the head position, accelerometers or optical tracking hardware may be used.[61,120]

A second key component of a teleoperation work station, or of a virtual environment, is a sensor for coupling hand position of the end-effector at a remote work site. The earlier mechanical linkages used for this coupling have been replaced by joysticks or by more complex sensors that can determine hand shape, as well as position. Modern joysticks are capable of measuring simultaneously all three rotational and three translational components of motion. Some of the joysticks are isotonic[121] and allow significant travel or rotation along the sensed axes, whereas others are isometric and sense the applied forces and torques without displacement.[122] Though the isometric sticks with no moving parts benefit from simpler construction, the user's kinematic coupling in his hand make it difficult for him to use them to apply signals in one axis without cross-couples signals in other axes. Consequently, these joysticks use switches for shutting down unwanted axes during use. Careful design of the breakout forces and detentes for different axes on the isotonic sticks allow a user to minimize cross coupling in control signals while separately controlling the different axes.[61,62]

Although the mechanical bandwidth might have been only of the order of 2–5 Hz, the early mechanical linkages used for telemanipulation provided force-feedback conveniently and passively. In modern electronically coupled systems force-feed-back or "feel" must be actively provided, usually by electric motors. Although systems providing six degrees of freedom with force-feedback on all axes are mechanically complicated, they have been constructed and used for a variety of manipulative tasks.[123,124] Interestingly, force-feedback has been particularly helpful in the molecular docking work at the University of North Carolina (see Fig. 16) in which chemists manipulate molecular models of drugs in a computer graphics physical simulation in order to find optimal orientations for binding sites on other molecules.[125]

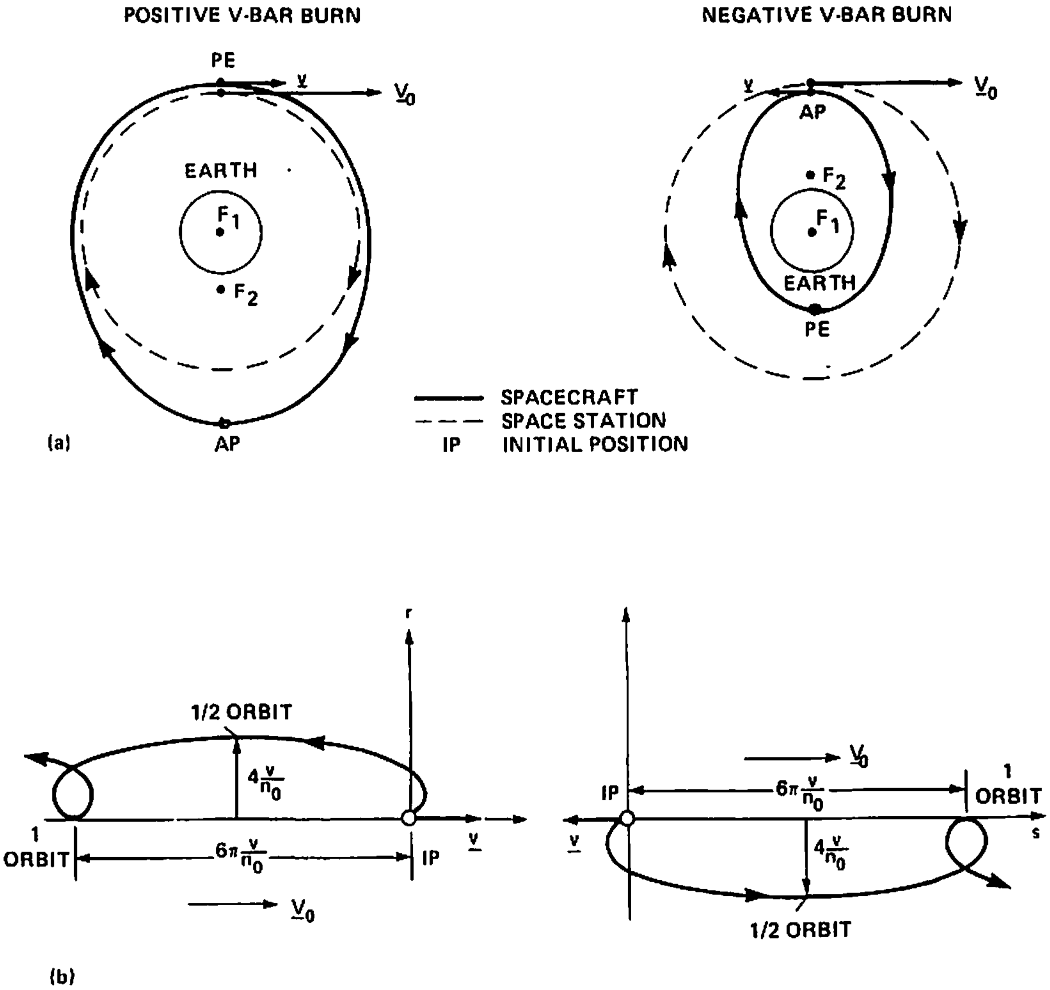

Fig. 12. Unusual environments sometimes have unusual dynamics. The orbital motion of a satellite in a low earth orbit (a) changes when thrust v is made either in the direction of orbital motion, V_0, (left) or opposed to orbital motion (right) and indicated by the change of the original orbit (dashed lines) to the new orbit (solid line). When the new trajectory is viewed in a frame of reference relative to the initial thrust point on the original orbit (Earth is down, orbital velocity is to the right; see lower panels), the consequences of the burn appear unusual. Forward thrusts (left) cause non-uniform, backward, trochoidal movement. Backward thrusts (right) cause the reverse.

High-fidelity force-feedback requires electromechanical bandwidths over 30 Hz. Most manipulators do not have this high a mechanical response. A force-reflecting joy-stick with these characteristics, however, has been designed and built (Fig. 17). Because of the required dynamic characteristics for high fidelity, it is not compact and is carefully designed to protect its operators from the strong, high-frequency forces it is capable of producing (see Refs 126–128 for some descriptions of typical manual interface specifications; and also see Ref. 129).

Manipulative interfaces may provide varying degrees of manual dexterity. Relatively crude interfaces for rate-controlled manipulators may allow experienced operators to accomplish fine manipulation tasks. Access to this level of proficiency, however, can be aided by use of position control, by more intuitive control of the interface, and by more anthropomorphic linkages on the manipulator.

An early example of a dextrous, anthropomorphic robotic end effector is the hand by Tomovic and Boni.[130] A more recent example is the Utah/MIT hand.[131] Such hand-like end effectors with large numbers of degrees of freedom may be manually controlled directly by hand-shape sensors; for example, the Exos, exoskeletal hand (see Ref. 132 and Fig. 19).

Significantly, the users of the Exos hand often turn off a number of the joints raising the possibility that there may be a limit to the number of degrees of freedom usefully incorporated into a dextrous master controller.[133] Less bulky hand shape measurement devices have also been developed using fiber optic or other sensors (Fig. 20);[134,135] however, use of these

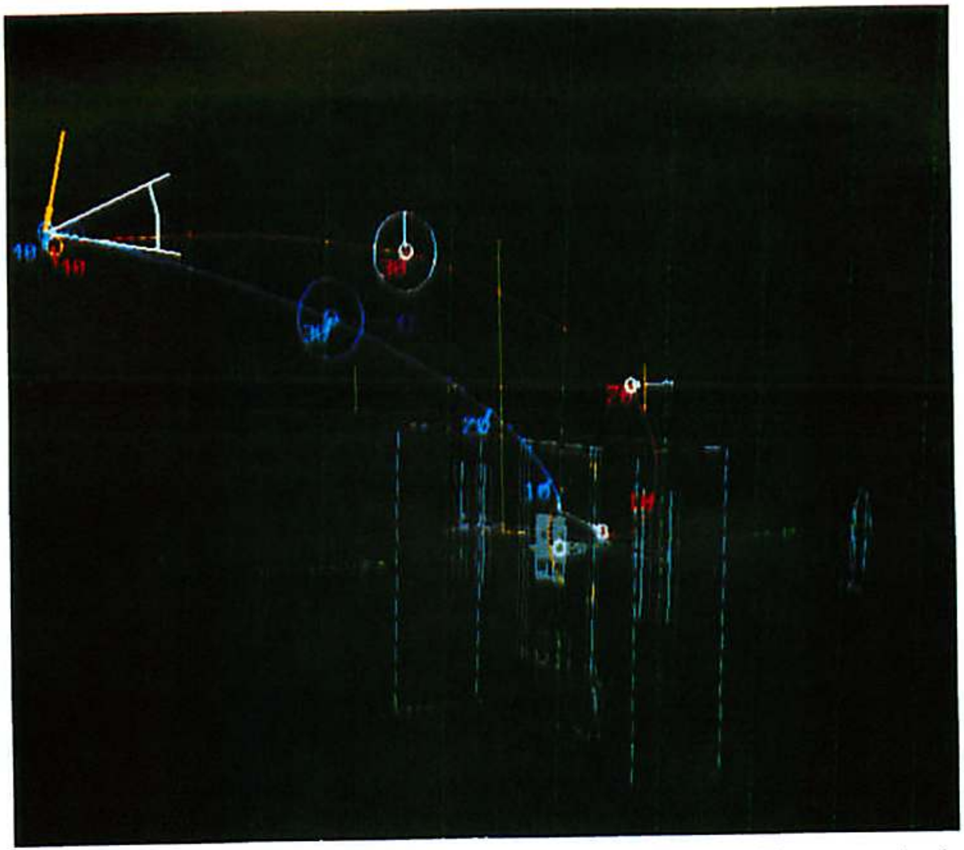

Fig. 13. Proximity operations planning display presents a virtual space that enables operators to plan orbital maneuvers despite counter-intuitive, nonlinear dynamics and operational constraints, such as plume impingement restrictions. The operator may use the display to visualize his proposed trajectories. Violations of the constraints appear as graphics objects, i.e. circles and arcs, which inform him of the nature and extent of each violation. This display provides a working example of how informed design of a planning environment's symbols, geometry, and dynamics can extend human planning capacity into new realms. (Photograph courtesy of NASA.)

alternatives involves significant trade-offs of resolution, accuracy, force-reflection and calibration stability as compared with the more bulky sensors (Figs 21–23).

3.6. *Photography, cinematography and video technology*

Since photography, cinema and television are formats for imagery that create synthetic environments, it is not surprising that technology associated with special effects for these media have been applied to virtual environments. The LEEP optics, which are commonly used in many "virtual reality" stereo-viewers, were originally developed for a stereoscopic camera system using matched camera and viewing optics to cancel the aberrations of the wide angle lens. The LEEP system field of view is approximately 110° × 55°, but it depends on how the measurement is taken.[137] Though this viewer does not allow inter-pupilary adjustment, its large entrance pupil (30 mm radius) removes the need for such an adjustment. The image pairs used, interestingly, are only 62 mm apart, closer together than the average inter-pupilary distance. This choice helpfully reduces the likelihood that users need to diverge their eyes to achieve binocular fusion.

An early development of a more complete environmental illusion through cinematic virtual space was Morton Heilig's "Sensorama". It provided a stereo, wide field-of-view, egocentric display with coordinated binaural sound, wind, and odor effects.[138] A more recent, interactive virtual space display was implemented by the MIT Architecture Machine Group in the form of a video-disk-based, interactive, map of Aspen, Colorado.[139] The interactive map provided a video display of what the user would have seen were he actually there moving through the town. Similar interactive uses of video-disk technology have been explored at the MIT Media Lab.[140] One feature that probably distinguishes the multimedia work mentioned here from the more scientific and engineering studies reported previously, is that the media artists, as users of the enabling technologies, have more interest in synthesizing highly integrated environments including sight, sound, touch and smell. A significant part of their goal is the integrated experience of a "synthetic place". On the other hand, the simulator designer is only interested in capturing the total experience insofar as this experience helps specific training and testing.

Fig. 14. Successive CAT scan X-ray images may be digitized and used to synthesize a volumetric data set which then may be electronically processed to identify specific tissue. Here bone is isolated from the rest of the data set and presents a striking image that even non-radiologists may be tempted to interpret. Forthcoming hardware will give physicians access to this type of volumetric imagery for the cost of an expensive car. (Photograph courtesy of Octree Corporation, Cupertino, California.)

3.7. *Role of engineering models*

Since the integration of the equipment necessary to synthesize a virtual environment represents such a technical challenge in itself, there is a tendency for groups working in this area to focus their attention on collecting the individual technologies. Accomplishment of specific tasks, however, places distinct performance requirements on the simulation. These requirements may be determined empirically for each task, but a more general approach is to use human performance models to help specify them. There are good general collections that can provide this background design data (e.g. Refs 141–143) and there are specific examples of how scientific engineering knowledge and computer-graphics-based visualization can be used to help designers conform to human performance constraints.[144–146] Useful sources on human sensory and motor capacities relevant to virtual environments are also available (see Refs 129, 147–151; and also Fig. 24).

Because widely available current technology limits the graphics and simulation update rate in virtual environments to less than 20 Hz, understanding the control characteristics of human movement, visual tracking, and vestibular responses is important for determining the practical limits to useful work in these environments. Theories of grasp, manual tracking,[27] spatial hearing,[148] vestibular response, and visual-vestibular correlation[88,152] all can help to determine performance guidelines.

Predictive knowledge of system performance is not only useful for matching interfaces to human capabilities, but it is also useful in developing effective displays for situations in which human operators must cope with significant time lags, for example those >250 msec, or other control difficulties. In these circumstances, accurate dynamic or kinematic models of the controlled element allow the designer to give the user control over a predictor which he may move to a desired location and which will be followed by the actual element (see Refs 15 and 18; and also Fig. 25).

Another source of guidelines is the performance and design of existing high fidelity systems themselves (see Refs 151–154; and also Figs 26 and 27). Of the virtual environment display systems, probably the one with the best visual display is the CAE Fiber Optic Helmet Mounted Display, FOHMD,[66,67] which is used in military simulators. It presents two 83.5° monocular fields of view with adjustable binocular

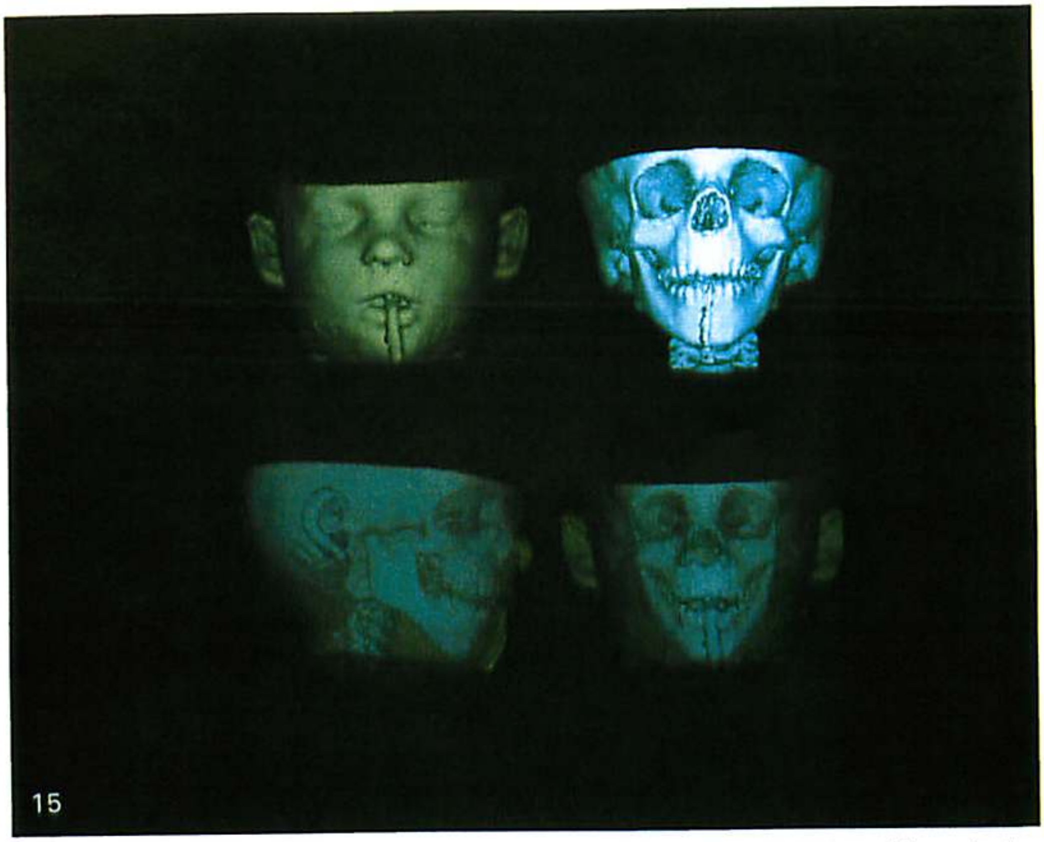

Fig. 15. Different tissues in volumetric data sets from CAT scan X-ray slices may be given arbitrary visual properties by digital processing in order to aid visualization. Here tissue surrounding the bone is made partially transparent so as to make the skin surface as well as the underlying bone of the skull clearly visible. This processing is an example of enhancement of the content of a synthetic environment. (Photograph courtesy of Octree Corporation, Cupertine California.)

overlap, typically about 38°, giving a full horizontal field-of-view up to 162°. The Wright–Patterson Air Force Base Visually Coupled Airborne Systems Simulator or VCASS display, which also presents a very wide field of view, has been used to study the consequences of field-of-view restriction on several visual tasks.[155] Their results support other reports that indicate that visual performance is influenced by increased field of view, but that this influence can become negligible at fields of view greater than 60°.[156]

A significant feature of the FOHMD is that the 60 Hz sampling of optical head position had to be augmented by signals from helmet-mounted accelerometers to perceptually stabilize the graphics imagery during head movement. Without the accelerometer signals, perceptual stability of the enveloping environment requires head-position sampling over 100 Hz, as illustrated by well calibrated teleoperations viewing systems developed in Japan.[157,158] In general, it is difficult to calibrate the head-mounted, virtual image displays used in these integrated systems. One solution is to use a see-through system, as illustrated by Hirose, and to compare the positions of real objects and superimposed computer-generated objects.[39]

Two integrated virtual environments systems for which performance and calibration data are not yet fully published are the NASA Ames Research Center's virtual interface[159] and the teleoperations interface at The National Advanced Robotics Research Centre, Salford, UK.[160] Technical descriptions and performance data for these and other virtual environment or visualization systems are likely to appear in journals cited in this paper, in this journal and in two new journals: *Presence: the Journal of Teleoperations and Virtual Environments*, MIT Press, Cambridge, Massacheucetts and *Pixel, the Magazine of Scientific Visualization*, Pixel Communications Inc., Watsonville, California.

4. VIRTUAL ENVIRONMENTS: PERFORMANCE AND TRADE-OFFS

4.1. *Performance advances*

With the state of off-shelf technology, it is unlikely that a fully implemented virtual environment display will today uniquely enable useful work at a price accessible to the average researcher. Those systems that have solved some of the major technological

Fig. 16. Researcher at the University of North Carolina uses a multidegree-of-freedom manipulator to maneuver a computer graphics model of a drug molecule to find binding sites on a larger molecule. A dynamic simulation of the binding forces is computed in real time so the user can feel these forces through the force-reflecting manipulator and use this feel to identify the position and orientation of a binding site. (Photograph courtesy of University of North Carolina, Department of Computer Science.)

problems, that is, adequate head-tracking bandwidth, viewing resolution comparable to existing CRT technology, do so through special purpose hardware that is very expensive. The inherent cost of some enabling technologies, however, is not high and development continues, promising improved performance and flexibility (e.g. optical head tracking[120] and high quality detailed volumetric display hardware for medium cost workstations stations, see Ref. 161). However, no matter how sophisticated or cheap the display technology becomes, there will always be some costs associated with its use. With respect to practical applications, the key question is to identify those tasks that are so enabled by use of a virtual environment display, that users will choose this display format over alternatives.

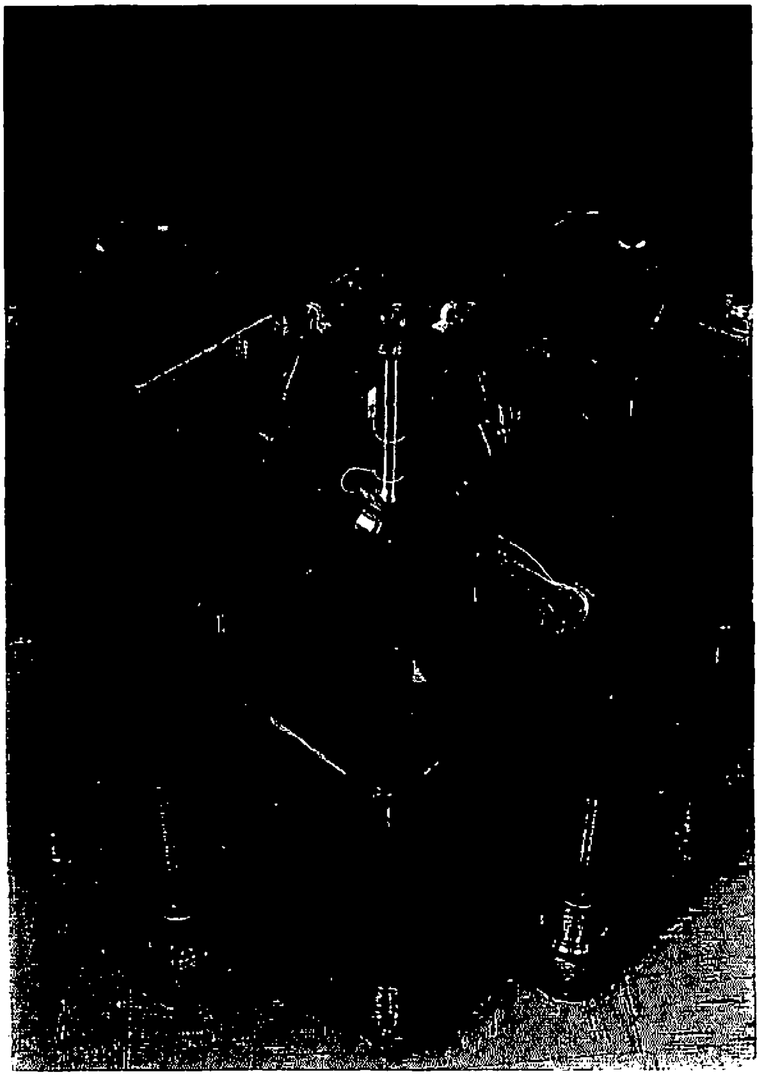

Fig. 17. A high-fidelity, force-reflecting two-axis joystick designed to study human tremor. (Photograph courtesy of B. Dov Adelstein.)

4.2. *Stereoscopic visual strain*

Designers of helmet-mounted displays for military applications have known that field use of stereoscopic displays is difficult because precise alignment is required to avoid problems with visual fatigue.[162,163] Accordingly, stereo eye strain is a likely difficulty for long-term use of stereo virtual environments. However, new devices for measuring acuity, accommodation, and eye position[164] may help improve designs. Development of a self-compensating display that adjusts to the refractive state and position of the user's eyes is one possibility. As with eye strain, the neck strain caused by the helmet's mass is likely to be relieved by technical advances such as miniaturization. But there will always be a cost associated with required use of head gear.

4.3. *Resolution/field-of-view trade-off*

Another cost associated with head-mounted displays, is that though they may generally have larger fields of view than the panel-mounted alternative, they will typically have correspondingly lower spatial resolution. Eye movement recording technology has been used to avoid this trade-off by tracking the viewer's current area of fixation so that a high-resolution graphics insert can be displayed there. This technique can relieve the graphics processor of the need to display high-resolution images in the regions of the peripheral visual field that cannot resolve it.[165] Reliable and robust eye tracking technology is still, however, costly, but fortunately may be unnecessary if a high resolution insert of approximately 30° diameter may be inserted. Since in the course of daily

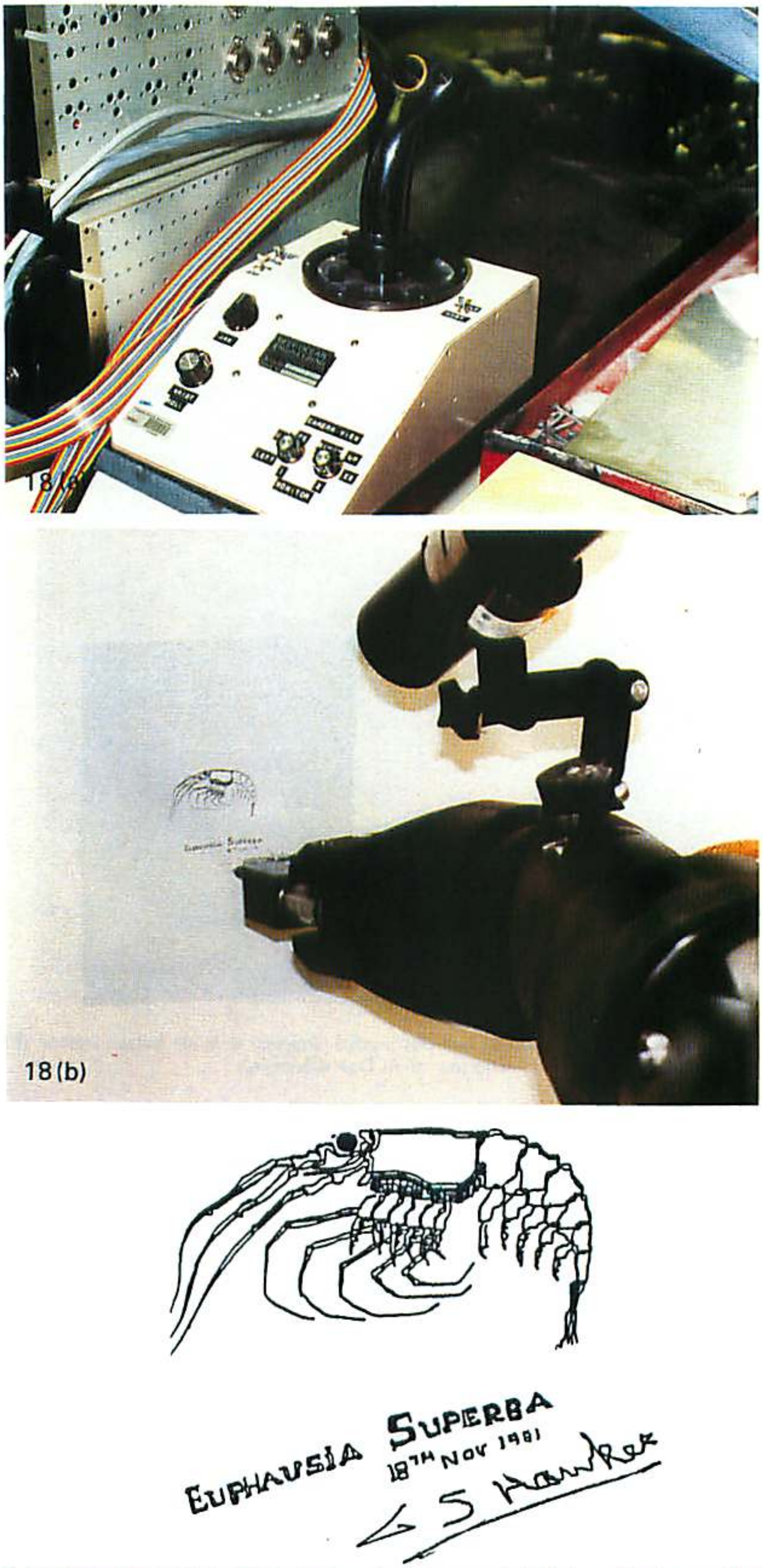

Fig. 18. Experienced operators of industrial manipulator arms (middle) can develop great dexterity (see drawing at bottom) even with ordinary two-degree-of-freedom, joystick interfaces (top) for the control of robot arms. Switches on the control box shift control to the various joints on the arm. (Photographs courtesy of Deep Ocean Engineering, San Leandro, California.)

Fig. 19. An exoskeletal hand-shape measurement system in a dextrous hand master which can drive a dextrous end-effector. (Photograph courtesy of Exos Inc., Burlington, Massachausetts.)

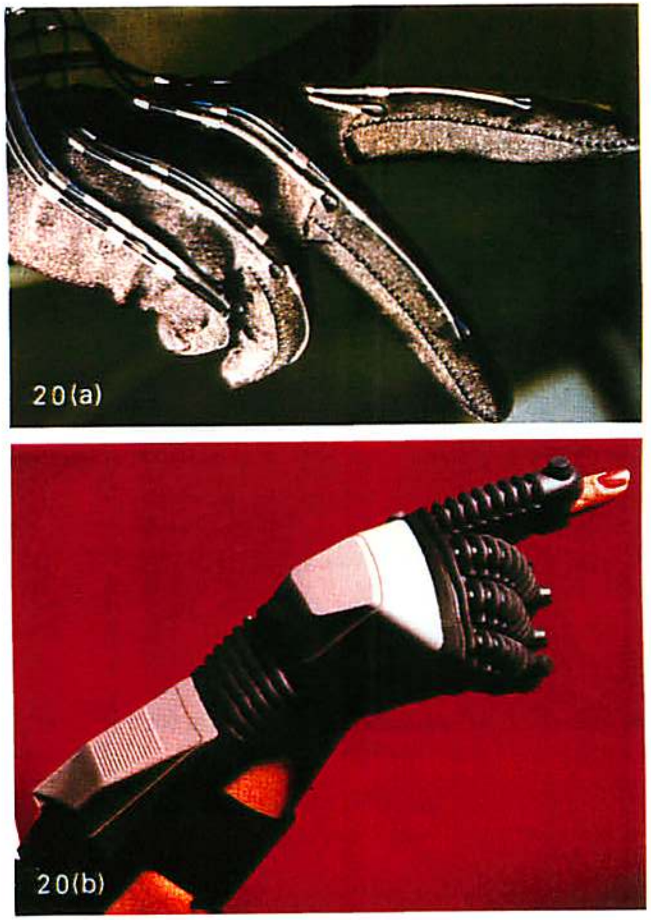

Fig. 20. Less bulky hand shape measuring instruments using flexible sensors (top panel: courtesy of VPL, Redwood City, California; bottom panel: courtesy of W. Industries, Leicester, U.K.).

Fig. 21. A six degree of freedom force reflecting joystick.[123] (Photograph courtesy of JPL, Pasadena, California.)

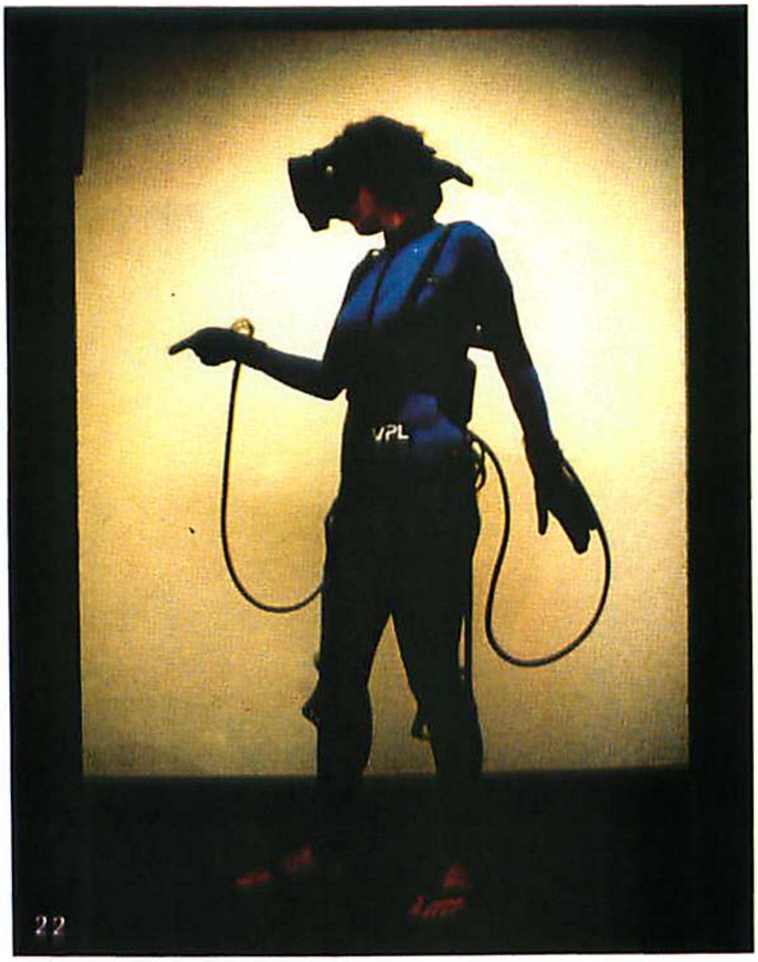

Fig. 22. Fiber-optic flexion sensors used by VPL in the DataGlove have been incorporated in a body-hugging suit. Measurements of body shape can be used to dynamically control a computer-graphics image of the body which may be seen through the head-mounted viewing device.[136] (Photograph courtesy of VPL, Redwood City, California.)

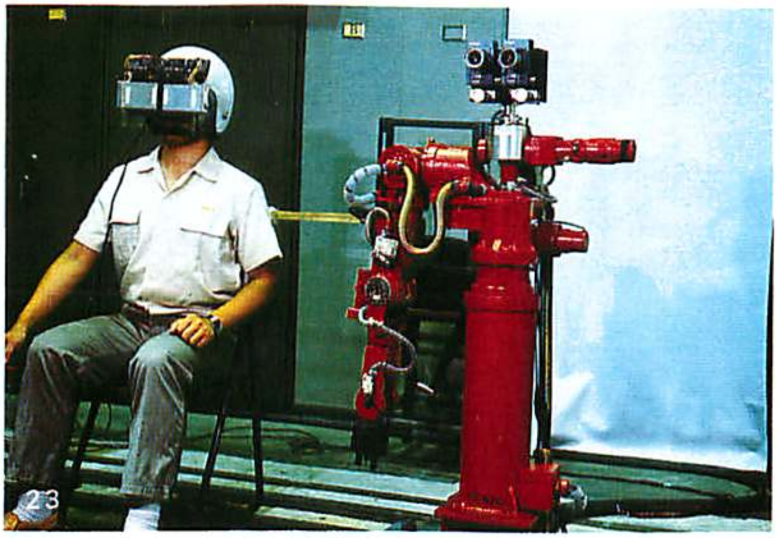

Fig. 23. Head and hand position sensors allow the user to control the head and arm position of a teleoperations robot which provides a stereo video signal that may be seen in the viewing helmet. (Photograph courtesy of Susumu Tachi.)

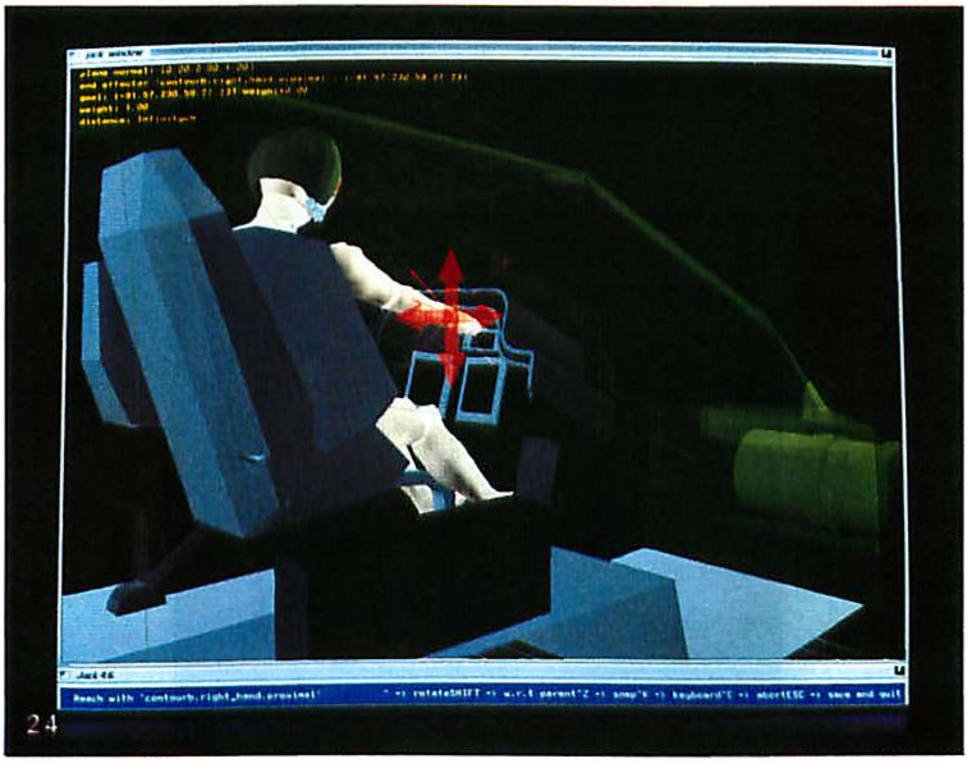

Fig. 24. "Jack" screen[145,146] example of a graphics display system that is being developed to assist cockpit designers to determine whether potential cockpit configurations would be consistent with human performance limitations such as reach envelopes or visual field characteristics. (Photograph courtesy of NASA.)

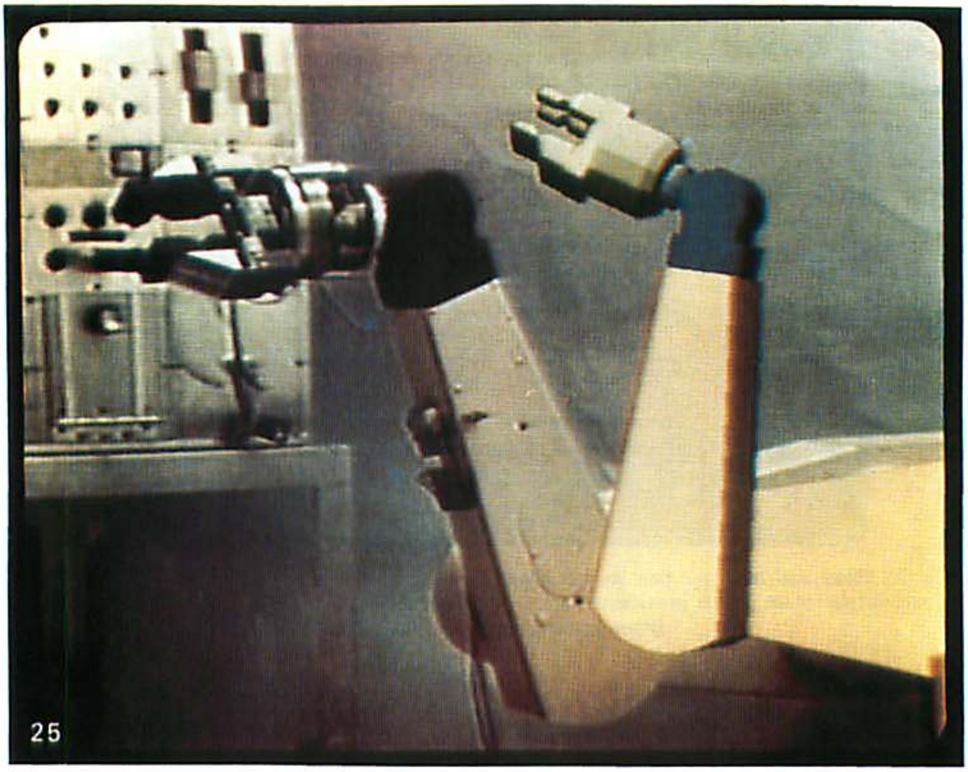

Fig. 25. Graphic model of a manipulator arm electronically superimposed on a video signal from a remote work-site to assist users who must contend with time delay in their control actions. (Photograph courtesy of JPL, Pasadena, California.)

Fig. 26. Visually Coupled Airborne Systems Simulator of the Armstrong Aerospace Medical Research Laboratory of Wright-Patterson Air Force Base can present a wide field-of-view stereo display (120° × 60°) which is updated at up to 20 Hz. Head position is measured electromagnetically and may be recorded at a slower rate Visual pixel resolution 3.75 arcmin/pixel. (Photograph courtesy of AAMRL, WPAFB.)

Fig. 27. Though very expensive, the CAE Fiber Optic Helmet Mounted display, FOHUD, is probably the best head-mounted, virtual environment system. It can present an overall visual field 162° × 83.5° with 5 arcmin resolution with a high resolution inset of 24° × 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. (Photograph courtesy of CAE Electronics, Montreal, Canada.)

life most eye movements may be less than 15°,[166] a head-mounted display system need not employ eye tracking if the performance environment does not typically require large amplitude eye movements.

4.4. *Unique capabilities*

In view of these and certainly other costs of virtual environment displays, what unique capabilities do they enable? Since these systems amount to a communications medium, they are intrinsically applicable to practically anything—education, procedure training, teleoperation, high-level programming, exploratory data analysis, and scientific visualization.[153] One unique feature of the medium, however, is that it enables multiple, simultaneous real-time foci of control in an environment. Tasks that involve manipulation of objects in complex visual environments and also require frequent, concurrent changes in viewing position, for example, laparoscopic surgery,[167] are tasks that are naturally suited for virtual environment displays. Other tasks that may be mapped into this format are also uniquely suitable. In selecting a task for which environment displays may provide useful interfaces it is important to remember that effective communication is the goal, and that consequently one need not aspire to creating a fully implemented virtual environment; a virtual space or a virtual image might even be superior. For non-entertainment applications, the illusion of an alternative reality is not necessarily the goal of the interface design.

4.5. *Future mass markets*

It is difficult to foretell the future practical mass-market applications for virtual environments. Like three-dimensional movies, the technology could only be a transient infatuation of visionary technophiles, but the situation is more likely analogous to the introduction of the first personal computer, the Altair. At its introduction, the practical uses for which small computers like it have become essential, word processing, data bases and spreadsheets, seemed well beyond its reach. In fact, spreadsheet programs like VISICALC had not even been conceived! Accordingly, some of the ultimate mass-market applications of virtual environments are likely to be unknown today. Possibly, once the world is densely criss-crossed with high bandwidth, public access, fiber-optic "information highways", mass demand will materialize for convenient, virtual environment displays of high resolution imagery.[168]

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