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Interfaces for Advanced Computing

Why should sophisticated computers be difficult to use? The coming generation of supercomputers will have the power to make elaborate "artificial realities" that facilitate user-computer communication

by James D. Foley

A flight simulator exemplifies the ability of modern computer technology to mimic reality. Computers orchestrate the sound, force and motion that approximate the aerodynamic behavior of an airborne plane, and specialized supercomputers provide the imagery. The convincing visual displays are particularly difficult to generate; supercomputers can be masters of illusion. Yet this mastery is rarely exploited in ordinary scientific applications.

Why confine the simulation capabilities of computer technology to the cockpit? Might not the machine that can re-create the sensations of flight also synthesize familiar contexts for scientific problems? Might it not build a communicative environment more natural than the customary typed commands and keyboard? In short, should it not be possible to program a computer to construct an "artificial reality" with which a user could interact?

For many computer scientists and engineers the answer to that question is an emphatic yes. Blueprints for artificial realities even more complex than flight simulations have already been drawn up. Interface technologies are being developed that will make supercomputers more responsive to human modes of communication including touch, gestures, speech and even a kind of eye contact. In addition to more realistic graphics displays, the next generation of supercomputers may feature hands-on manipulation of computer-generated images along with tactile sensations and force feedback. Sensors will measure the position of a user's head and track the movements of his eyes; voice-recognition programs will allow computers to interpret spoken language.

Researchers hope that artificial realities will make learning about and exploiting a supercomputer's capabilities more efficient and enjoyable. These elaborate interfaces might do for scientists and engineers what spreadsheet programs such as Lotus 1-2-3 have done for accountants. Of course, artificial realities hold more promise for some problems than for others; it is hard to imagine, for instance, how desktop publishing would benefit from three-dimensional representation and wall-size screens. On the other hand, many scientific problems, particularly those that can be represented in three dimensions, call out for a greater degree of interaction between man and machine.

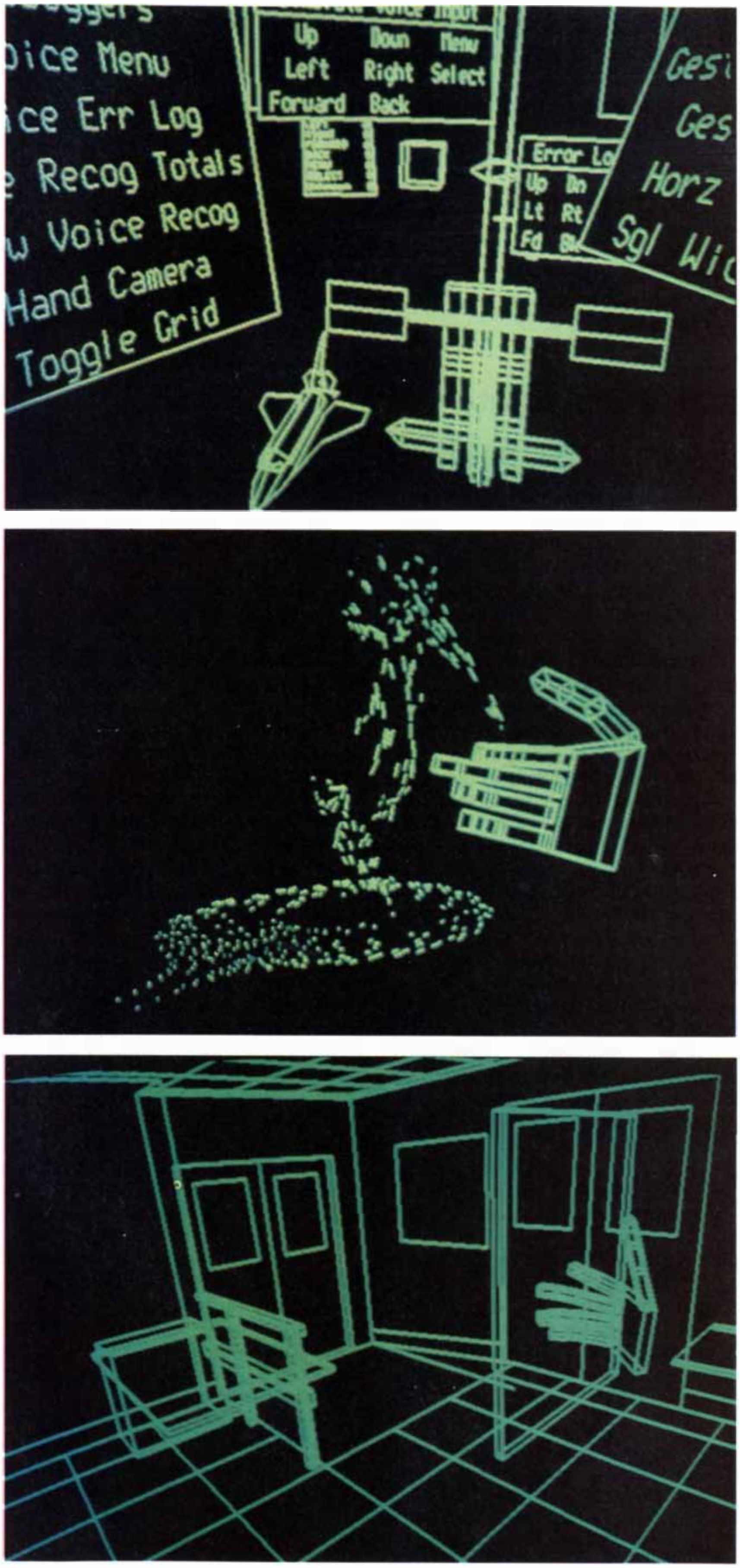
The interface between the user and the computer may be the last frontier in computer design. In the past few years hardware costs have fallen dramatically; software costs are also decreasing, albeit less rapidly. Techniques for maximizing computer efficiency and minimizing the use of memory have largely been established, although they are constantly being refined. What remains to be addressed is the maximization of user efficiency.

Scientific computing in particular has been forced to focus on hardware performance because its computational needs are so great. With the coming generation of supercomputers, that focus may finally be allowed to change. A Cray-2, currently one of the fastest computers in the world, can perform 1,000 million floating-point operations per second (MFLOPS). (FLOPS are a standard industry measure of computational speed; personal computers run at speeds of anywhere from 1,000 to 100,000 FLOPS.) The coming generation of Crays, slated to appear next year, will run 10 times faster. Even the workstations that provide graphics for supercomputers are becoming more powerful: a workstation Stellar Computer Inc. expects to release by January will operate in the 50-MFLOPS range.

How can this additional power make the interaction between user and computer more like cooperation than confrontation? Obviously an increase in the speed of computation is a boon in itself, decreasing and in some cases eliminating the waiting period during which the computer generates results. Less obvious are the means for coupling supercomputer users more tightly to the problem-solving process.

Currently, using a typical supercomputer is a bit like consulting a machine-age oracle. There is a period of preparation during which a problem is defined and its parameters are specified on a workstation. The workstation organizes the problem in a form appropriate for the supercomputer; its ensuing compu-

HEAD-MOUNTED MONITOR with a position and orientation sensor, gloves that track hand and finger movements and a microphone wired for voice recognition transport the user to a computer-generated reality. The user issues instructions to the computer by pointing, talking, gesturing and actually handling graphics images. Workers at the National Aeronautics and Space Administration's Ames Research Center have constructed several artificial realities for use in this system (*see illustration on next page*).



tations can take seconds, hours or days. In many cases the user cannot interrupt or alter the computations once they have begun, and if the results suggest checking alternative parameters, the ritual must be repeated from the start.

The advent of artificial realities, foreshadowed by flight simulation, will fundamentally change the way a person works with a supercomputer. Artificial realities allow the user to interact with the computer in an intuitive and direct format and to increase the number of interactions per unit of time. The ultimate objective of artificial-reality research is to develop a simulated environment that seems as "real" as the reality it depicts. The profoundest strength of the interfaces, however, may lie in their ability to go beyond reality itself, by modeling in concrete form abstract entities such as mathematical equations and by enabling users to surmount problems of scale in manipulating atoms and galaxies alike.

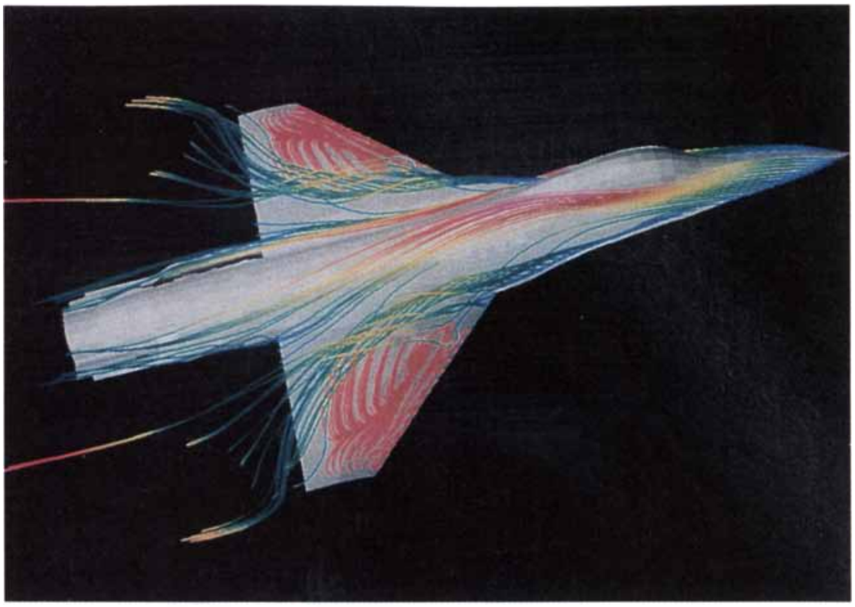
Artificial realities have three components: imagery, behavior and interaction. Realistic visual *imagery* helps the user to interpret the information being presented by the computer. The images may represent real objects, such as building frames, or abstractions, such as patterns of fluid flow. These images *behave* the way the objects or abstractions they represent would behave. Behavioral modeling exacts the heaviest computational toll, because it often entails solving extensive sets of equations over and over again. Finally, the user *interacts* with an artificial reality in much the same way as he interacts with the three-dimensional world: by moving, pointing and picking things up, by talking and observing from many different angles.

The interactive component of artificial realities lags behind the other

GRAPHICS DISPLAYS projected inside the helmet shown on page 126 include menu interfaces (*top*), airflow patterns (*middle*) and the laboratory housing the system (*bottom*). These photographs only hint at the realism of actual displays, which provide depth cues by showing each eye a view from a slightly different perspective and also allow the user to pan across the computer-generated environment by turning his head. The user can select a menu option with a word or a gesture, turn an airflow model to look at it from another angle or reach out and "touch" the laboratory's walls and desks.

components. Commercial technologies for viewing and manipulating in three dimensions are still relatively primitive. What kinds of interactive devices will restore the balance?

I shall begin by addressing the most familiar component of the computer interface: the display monitor. The typical computer workstation is equipped with a 19-inch-diagonal color monitor; viewed from a distance of two feet, the display subtends 37 degrees of visual field horizontally and 28 degrees vertically. Yet the visual field of one eye, assuming the head is fixed, spans 180 degrees horizontally and 150 degrees vertically. Displays that fill the visual field give the observer a sense of being part of a scene rather than on the outside looking in: witness the IMAX and OMNIMAX wide-screen motion-picture systems. Hence wall-size projections of computer screens could help to immerse the user in an artificial reality.



SIMULATION OF AIRFLOW PATTERNS generated by an F-16A fighter jet exemplifies the sophistication of current supercomputer graphics. The path of air and its elevation above the body of the aircraft are indicated by colored streaks: blue signifies low elevations, red high. Red swirls on the wings reveal areas of shear stress. The information this image provides helps engineers to design aircraft that have less drag and more lift. Equally refined graphics are already standard features of many artificial realities.

Although a larger display better fills the visual field, it will show no more detail if it uses the same number of pixels, or picture elements. Pixels are the discrete points of light that make up a cathode-ray-tube image; they define the resolution of an image. A typical workstation monitor consists of roughly a million pixels arranged in a 1,280-by-1,024-pixel grid. At viewing distance each pixel subtends about two minutes of the visual field, but the human eye can distinguish detail down to one minute. Currently a 20-inch-square color monitor is available with approximately four million pixels in a 2,000-by-2,000 grid; viewed from a distance of two feet, each pixel subtends an angle of roughly 1.4 minutes. A monitor that fully exploits the acuity of human vision at normal viewing distance has yet to be constructed.

Given these limitations, how else can realism be improved? One alternative is the head-mounted display. This display can facilitate depth perception in much the same way as a Vu-Master achieves its stereoscopic effect: each eye is provided with a slightly offset view of the same image. Other depth cues come from motion parallax, the phenomenon that describes the shift in background that occurs when an observer looking at a point in space changes position. This effect is achieved with the aid of a sensor that registers head position and orientation. Furthermore, because the sensor recognizes gross head movements, the user can enjoy the illusion of scanning an artificial panorama as he turns his head. The images he sees depend on the direction in which he is facing.

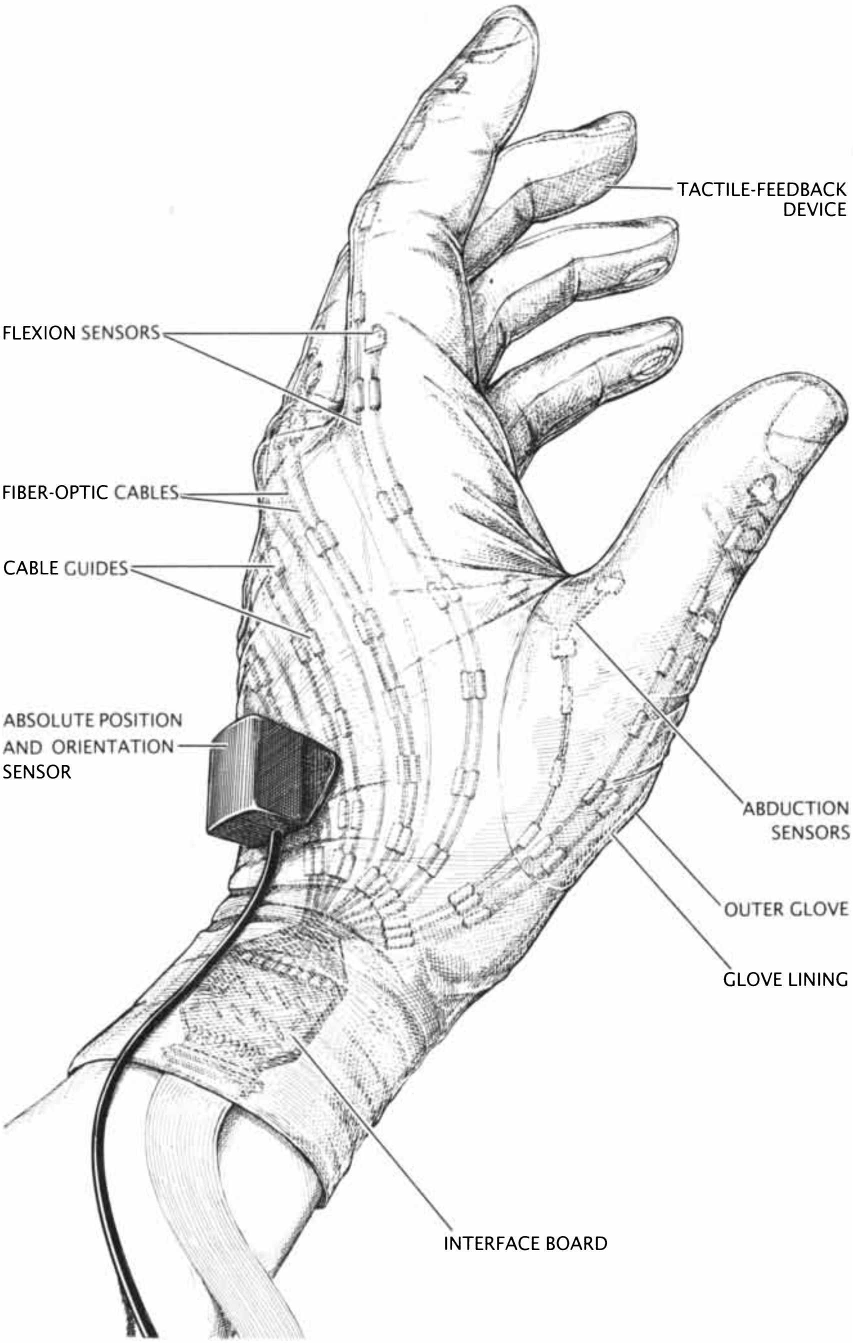
In the first head-mounted display, built by Ivan E. Sutherland in the 1960's, miniature cathode-ray tubes acted as displays and mechanical linkages relayed head position and orientation to the computer. Today lightweight liquid-crystal monitors and electronic sensors have made implementation more practical. The most advanced system incorporating these features not only creates artificial realities but also replaces one reality with another. At the Ames Research Center of the National Aeronautics and Space Administration, Scott S. Fisher, Michael W. McGreevy and James C. Humphries have constructed a helmet to be worn in the space station that would project to an astronaut inside the station what a robot operating outside the station "sees." When the astronaut's head turns, the robot's camera eyes swing in the same direction.

The electronic sensor that registers head position and orientation in the NASA system figures importantly in many other interface systems. Manufactured by the Polhemus Navigation Sciences division of the McDonnell Douglas Corporation, the sensor works by sending electromagnetic pulses from three transmitter antennas to three receiver antennas. In both the transmitter and the receiver units the antenna coils are at right angles to one another, forming a Cartesian-coordinate system.

The transmitter is a box roughly two inches on a side that must be placed within five feet of the receiver. It emits three pulses in sequence, one from each antenna. The pulses induce a current in the coils of the receiver, a cube less than an inch on a side that is placed on the object being tracked. The strength of the current depends both on the distance the receiver is from the transmitter and on the relative orientation of the transmitter and receiver coils. A computer can calculate the three-dimensional position of the receiver unit from the nine current values resulting from three successive pulses. The three pulses are repeated about 40 times per second and the resulting images move somewhat erratically; smooth simulated motion probably will not be possible until the sensor can produce 60 pulsed triplets per second.

Installed on the NASA helmet, the Polhemus sensor would be rather adept at determining the direction of a user's gaze except for one catch: the eyes can and often do move independently of the head. To surmount this difficulty engineers are exploring a technology borrowed from experimental psychology. Psychologists have long used devices called eye trackers to gather data on how people read and examine pictures. Eye trackers bounce a beam of light off the cornea of the eye. The direction in which the light is reflected indicates where the user is looking: the point of regard.

Eye trackers are still quite new to the computer scene. Trackers that attach to eyeglasses can be had for a few thousand dollars, but they are not very accurate. A more elaborate system projects a pinpoint of infrared light onto the cornea and detects its reflection with a wide-angle television camera placed approximately three feet from the user. The camera stays locked on the eye in spite of considerable head movement unless the movement is quite rapid; it might be baffled, for instance, by a sneeze.



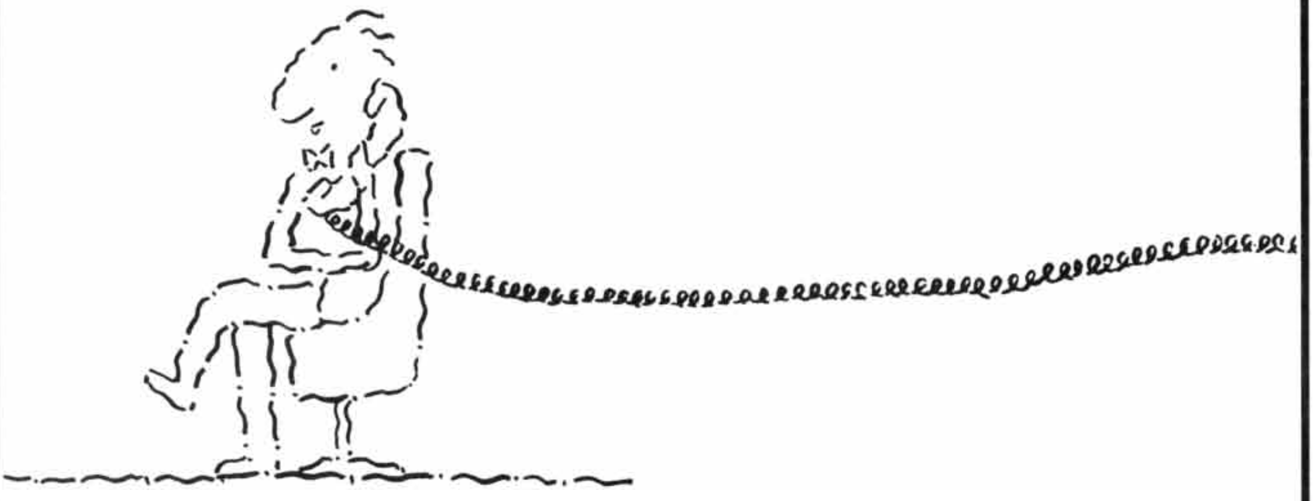
DATAGLOVE developed by VPL Research, Inc., translates hand and finger movements into electrical signals. Between two layers of cloth, fiber-optic cables anchored at both ends to an interface board run the length of each finger and double back. Each cable has a light-emitting diode at one end and a phototransistor at the other. Cables are treated so that light escapes when a finger flexes; the phototransistor converts the light it receives into an electrical signal. The position and orientation sensor is made by the Polhemus Navigation Sciences division of the McDonnell Douglas Corporation.

Wall-size screens, head-mounted displays, position sensors and eye trackers can improve the credibility of an artificial reality by broadening the visual field and by enhancing detail at the point of regard. The displays can present actual images, as NASA's space-station helmet will, or the artificial images generated by a supercomputer. How will the user interact with such displays?

Most current interaction devices are limited to two dimensions. Even manipulations of three-dimensional computer simulations must be specified through a two-dimensional medium, either a mouse or a joystick. Worse yet are dials that separately control the three axes. Suppose an interaction device could be made that combined the precision, control and agility of the human hand. Actually such a "device" is available: it consists of the hand itself, equipped with a Polhemus sensor and a special glove that can record hand and finger movements.

The DataGlove was developed in the past three years by Thomas G. Zimmerman and L. Young Harvill at a small California company called VPL Research, Inc. Fiber-optic cables sandwiched between two layers of cloth run the length of each finger and thumb. Both ends of each cable are anchored in an interface board near the wrist. An LED (light-emitting diode) at one end sends light down the shaft of the cable to a phototransistor at the other end. The phototransistor converts light into an electrical signal a computer can recognize; the signal travels from wrist to terminal through electrical wire. Although ordinary fiber-optic cables will transmit light when they are bent, the cables in a DataGlove are treated at the sites where fingers flex so that light escapes when a finger is crooked, or when, say, the user moves his thumb toward his forefinger. The greater the movement is, the more light is lost.

Coupled with a Polhemus sensor, which can be mounted on the back of the hand, the DataGlove has exciting potential. Fisher's group at Ames uses the glove in conjunction with the space-station helmet; NASA hopes that one day a robot outside the station will be able to carry out complex maneuvers and repairs by mimick-



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ing the hand movements of an astronaut inside the station. VPL is also incorporating DataGlove principles in a DataSuit that covers the entire human frame.

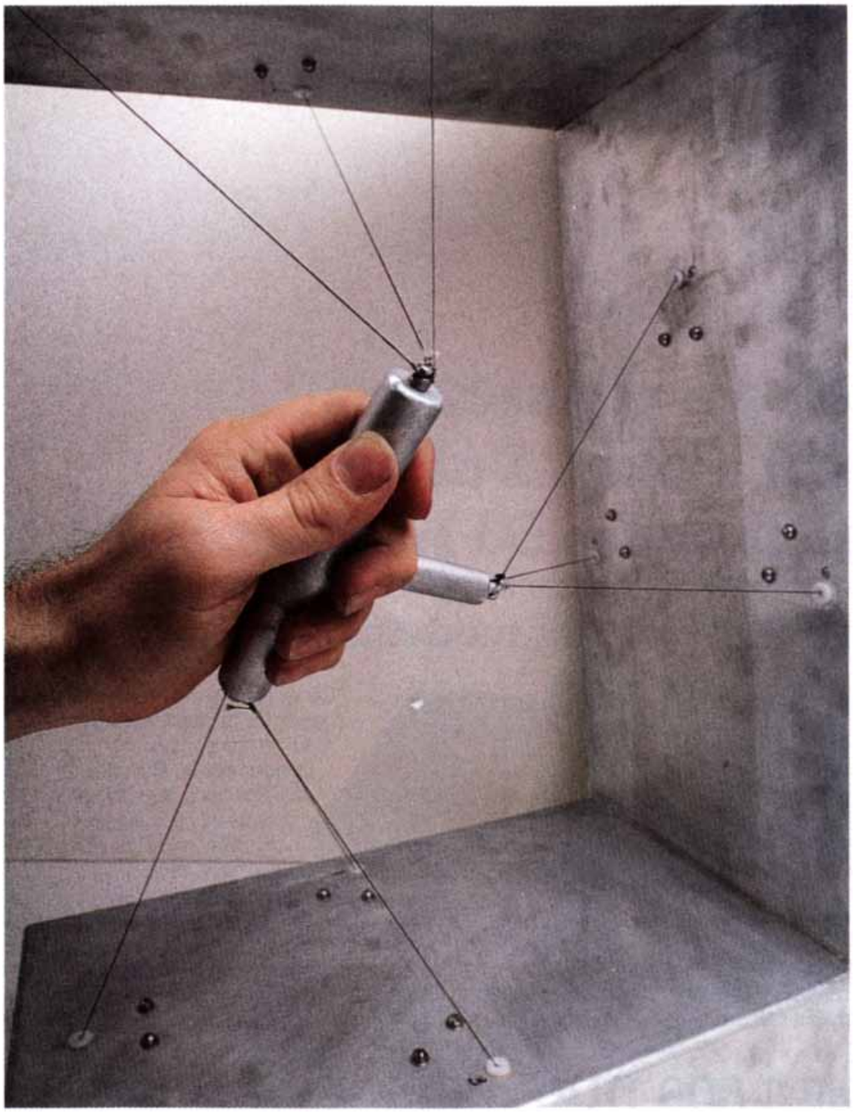
An interface as complex as the DataGlove may not make sense for every kind of problem, but many of the scientific equations that are presented to supercomputers model systems that are easier to deal with directly than by typed commands. Furthermore, artificial realities can add a tactile element to systems that cannot ordinarily be touched. For instance, imagine a biochemist examining two molecules: an enzyme and the substrate to which it binds. He knows the structure of both the enzyme and the substrate, and both molecules are displayed on a computer monitor. The chemist wants to find out what part of the enzyme interacts with what part of the substrate. Armed with a DataGlove, he could quickly manipulate both molecules like two pieces of a jigsaw puzzle to see what parts fit together.

Now imagine being able to feel the topography of the enzyme molecule: its crevices and projections, its smooth edges and sharp corners. Imagine probing with a finger the enzyme's active site, which exerts a strong chemical attraction on the substrate. Imagine maneuvering the substrate close to the active site and feeling the pull of the interatomic forces that join the two! In order to achieve these effects engineers are exploring methods for creating tactile and force feedback.

Three technologies for tactile feedback are being tested that could be incorporated in the DataGlove design. One technology is adapted from a tactile-feedback device for the blind in which small solenoids push blunt wires against the skin. This type of actuator, however, is probably too large: each is about a third of an inch thick. Piezoelectric crystals can also be employed in conjunction with the glove. The crystals vibrate when they are activated by an electric current, and the mind interprets their vibration as pressure. A third approach exploits the new "memory metals" that change shape with temperature. Small insulated pieces of this metal could be oriented to push against the skin when they are heated by an electric current.

The sensation of force is more difficult to convey in a glove device than tactile sensation, although memory metals offer some promise here as well. As long ago as 1968 a group directed by Frederick P. Brooks, Jr., of the University of North Carolina at Chapel Hill adapted for force feedback a remote manipulator device of the kind used to handle radioactive materials. Today the most effective force-feedback system is the "joystring" built by Richard J. Feldmann of the National Institutes of Health. Named after its predecessor, the joystick, Feldmann's joystring is a simple rigid T about three inches long connected at each end to three taut wires. The wires are in turn connected to shaft encoders and servomotors. The user grips and manipulates the joystring T; the computer reads the user's hand movements through the shaft encoders and generates force and torque feedback by means of the servomotors.

In addition to the joystring, only a handful of force-feedback devices have been made, each one unique. The systems have been limited to specialized applications in research laboratories. Simpler designs can respond to force input but cannot generate force feedback. At George Washington University my colleague John L. Sibert and his group have developed a novel application of such a force-input system. They have devised a paint system for artists based on a commercially available data tablet that senses not only the position of a stylus but also the orientation of and force applied to the stylus. A computer uses this information



JOYSTRING is one of the more effective force-feedback devices. Designed by Richard J. Feldmann of the National Institutes of Health, the apparatus relays to a computer the position of a hand grasping the suspended T; the supercomputer in turn directs servomotors to exert force through differential tension on the nine wires connected to the T.

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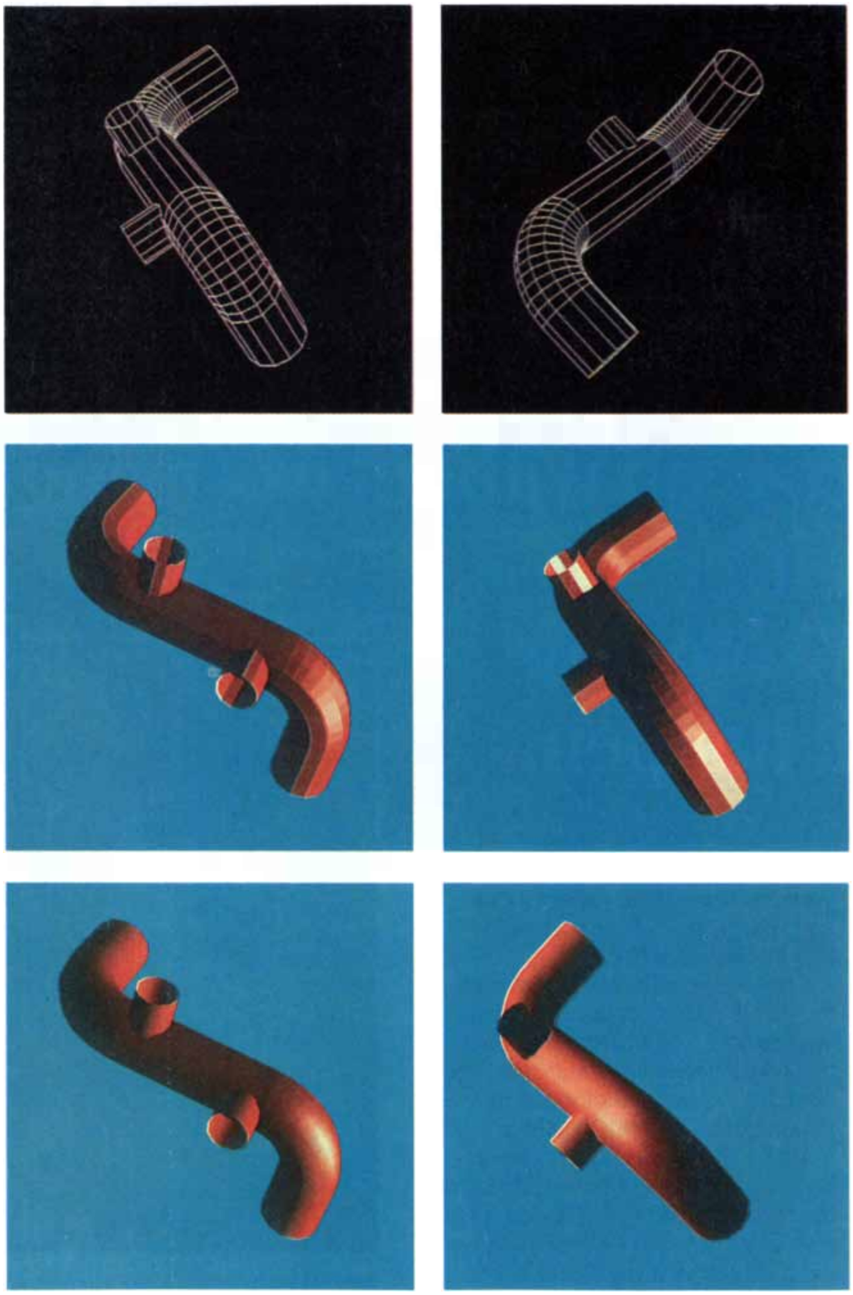
to simulate the behavior of a paintbrush. As downward pressure increases, the "brush" spreads out and the width of the line being drawn changes with the orientation of the stylus. Sibert's artificial reality reflects to some extent the artist's traditional tools, but it also creates artistic tools that until now have not existed.

In what other ways might a user want to interact with a supercomputer? In many cases talking or gesturing to a computer may be more appropriate or convenient than nonverbal manipulations of symbolic images. Both voice- and gesture-recognition systems are further advanced than the other components of artificial realities. More than 10 years ago Nicholas Negroponte and Richard A. Bolt of the Massachusetts Institute of Technology demonstrated the feasibility of voice recognition in computer interaction. Now machines with vocabularies of several hundred words are routine co-workers in jobs requiring use of both hands, such as the testing of electronic assemblies.



ROTATED PIPES helped the author to explore how realism affects a user's performance. Subjects shown two images side by side were asked whether or not one image was a rotation of the other. The author found that users compare pipes that are colored in and highlighted (*middle*) about 20 percent faster than they compare outlined figures (*top*), but that further refinement (*bottom*) does not significantly improve comparison.

The technology for voice recognition simply has not yet been integrated into most computer problem-solving environments. This unfortunate procrastination in adopting new technology has occurred in the past: the mouse, developed in the late 1960's, was not commercially available until early in the 1980's. Meanwhile voice-recognition systems are becoming more sophisticated. Kenneth Davies of the IBM Corporation's Thomas J. Watson Research Center recently demonstrated to me an experimental system with a vocabulary of 20,000 words—about 98 percent of the typical English speaking vocabulary. The machine can even interpret phonetically abstruse phrases such as "Write Ms. Wright a letter right away." IBM expects to make its system affordable within a few years.

The technology for gesture recognition has been languishing for several years with some difficulties waiting to be ironed out. Systems must be taught to sort through ambiguities in strings of gestures and to discern when one command ends and the next begins. James R. Rhyne of the Watson Research Center has developed a system that recognizes hand gestures made in two dimensions with a penlike positioning device. In a spreadsheet application the user can total two groups of numbers by circling each group on a data tablet and making a summation sign. The computer enters the total at the position on the spreadsheet indicated by the summation sign. Although this technology is still in its infancy, I can envision a day when a biochemist clad in DataGloves gestures at molecular conformations on a supercomputer display and says, "The phenylalanine 221 on this helix [pointing] doesn't interact properly with this [circling] glutamine 57. Change it to a histidine."

Artificial realities are well on their way—in fact, one of the most difficult hurdles remaining involves integrating technologies that have already been established. Once this hurdle has been cleared, the gadgets themselves will require a relatively small investment; a DataGlove, for instance, costs about $8,000. Indeed, the research and programming effort currently expended on advanced interfaces will probably be the most expensive aspect of their implementation. Will the benefits of artificial realities justify the cost?

Instinctively it would seem that a system inviting user interaction and presenting information in accessible formats would be much faster, more instructive and easier to learn than conventional interfaces. This kind of hunch is very difficult to quantify. Would a materials engineer understand a stress analysis better if he could apply the stress with his own hand? Will molecular interactions become more obvious if their forces can literally be felt? And how "real" do artificial realities need to be to accomplish their purpose?

I began to ask this last question as it pertains to visual imagery some time ago. Working with my colleague Woodrow Barfield and a graduate-student team led by James W. Sandford, I examined experimentally the effect of increased realism on the speed with which computer users carry out a simple mental manipulation of two images. The task, called mental rotation, is commonly presented to subjcts by experimental psychologists studying how people represent images in their minds. My subjects were shown two different images of pipelike structures side by side and asked to decide whether or not one image was a rotation of the other. In some tests the images were only outlined; in another set they were colored in and highlighted, and in a third, colored and highlighted images were given smoothly shaded surfaces. We found that users can compare colored-in images about 20 percent faster than outlined figures, but that the more sophisticated shaded representations did not improve comparison time any further. Hence there may sometimes be a limit to how "real" artificial realities must be.

As for questions about the ultimate value of artificial realities, the answers are still to come. Nearly 20 years ago Brooks's graduate student James J. Batter noted that some students studying graphic displays of two-dimensional force fields gained a better understanding of the concepts involved if they could not only see the force vectors but also feel them. Batter's study, which used a simple two-dimensional force-feedback device, is the most recent example of research assessing the worth of artificial realities. Along with my experiments at George Washington University, it illustrates the type of research needed to determine whether the promise of artificial realities is more than an illusion.