It Just Feels Right

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Tools that add the sense of touch to the computer desktop are providing users with a sense of reality

Mark Hodges

Most computer users are so accustomed to keyboards and mice that they forget how awkward these instruments can be for manipulating graphically rendered objects on a screen. This limitation has become increasingly apparent as improvements in 3D visualization push simulation to the desktop. The more lifelike and immersive graphical displays become, the more tempting it is to explore the data-like objects in the real world--by touching as well as seeing and hearing. The problem, however, rests with the computers themselves in that they offer little facility for tactile sensation.

As 3D visualization becomes more widely used throughout industry, the inability to "touch" virtual objects is a noticeable shortcoming. While many tasks require only sight and sound, other work calls on the use of tactile sensations, sometimes relying primarily on the sense of touch. For instance, mechanics cannot always see what they need to fix; they must use their hands to reach inside an engine and feel their way to the right component. Engineers and managers cannot assess how easily a vehicle design can be maintained or manufactured unless they can feel spatial relationships among parts in a virtual assembly. And doctors cannot realistically practice surgical procedures in simulators without touching replicas of body tissues.

Through haptics--the technology that provides sensing and control via touch and gesture--computers are adding what McGill University professor Vincent Hayward calls a new "mechanical channel" for accessing and manipulating data normally available only through a visual means. "The keyboard is completely passive--it can`t give you any

information," explains Hayward, who is also a prominent researcher and a founding partner of Haptic Technologies in Montreal, Canada. "A good interface would be programmable. That`s essentially adding another channel of human/computer communication."

Virtual touch on the desktop, however, is no far-off dream. Computer games already include simple simulations of physical forces, and in the next year consumers will be able to buy a low-cost mouse that makes graphic objects on desktops tactile. Animators using one popular software package can now simulate the feel of a brush painting a surface, and incoming residents at a Pennsylvania medical school are practicing suturing techniques with a haptic surgical simulator. In the near future engineers will be able to build computer-aided designs with models whose surfaces can be touched as well as seen.

Proponents of the technology believe it can open a world of new possibilities for computer modeling, work training, education, entertainment, engineering, management reviews, product marketing, graphic arts, and adaptive devices for the blind. But establishing this new channel for representing information isn`t proving easy; tactile sensation is much more difficult to simulate than visual or audio senses. "Unlike our other sensory modalities, haptics relies on action to stimulate perception," according to Kenneth Salisbury, a principal research scientist at MIT`s Artificial Intelligence Laboratory and coinventor of SensAble Technologies` PHANToM haptic interfacing device. "To sense the shape of a cup we do not take a simple tactile snapshot and go away and think about what we felt. Rather, we grasp and manipulate the object, running our fingers across its shape and surfaces in order to build a mental image of a cup."

A haptics system must sense and analyze the forces applied by a user, then deliver a physical sensation back to the person--all in real time. Systems of this kind provide force feedback, and the need to track force and generate response on a continual basis poses a heavy and sometimes unresolvable computational burden. This technical problem is complicated by the need of most applications to provide force-feedback sensations in multiple dimensions. For users to touch all sides of a virtual 3D object, the haptics system must represent information over three axes (or degrees of freedom). For users to turn virtual objects freely and feel them rotate, the system must generate feedback over another three degrees of freedom.

A variety of interfacing devices--some simple, others highly complex--for conveying different types of force-feedback applications have made it into the commercial sector. For computer gaming and general computing, engineers have developed special-purpose joysticks, steering wheels, flight yokes, and computer mice to offer one- or two-dimensional tactile sensations. For applications requiring 3D-position sensing and feedback, they have designed a finger thimble and pen-like stylus. For tasks requiring hand-grasping actions or whole-hand sensitivity, developers have provided gloves with sensors embedded in their fabric or transmitted to the gloved hand through an exoskeletal frame.

Until the early 1990s, only a few force-feedback systems were available, and they were so costly and specialized that their market was limited to military-simulation research groups. The first company to attract broader attention was SensAble Technologies, a Cambridge, Massachusetts, firm that commercialized its PHANToM system in 1993 at a low-end cost of approximately $20,000. Although this price represented a breakthrough for its day, the primary customers for haptics systems were researchers in military agencies, corporations, and universities who were still trying to get a handle on how the technology could be used.

SensAble became widely known for its 3D force-feedback device that lets users touch and manipulate objects in three dimensions with a fingertip or a stylus, but it wasn`t alone in commercializing haptics technology. Immersion Corporation (San Jose, CA) has emphasized low-cost applications of haptics in gaming devices and computer mice. Cybernet Systems (Ann Arbor, MI) has developed numerous custom systems for military and industrial clients, including the largest force-feedback system ever made. Haptic Technologies has marketed a series of haptic pens and mice used primarily for research and computer use by the blind. Virtual Technologies (Palo Alto, CA) has developed CyberGrasp and CyberTouch gloves that provide force feedback to the hand and all five fingers so that grasping applications can be simulated.

Low-Cost Applications

In the past year, haptics broke into the mainstream consumer market. A high point occurred when Immersion introduced I-Force, a technology that integrates force feedback into computer games. Players can hold haptic joysticks or other hand-held guidance devices and enjoy vibrations, sloshing, jolts, and other physical sensations while navigating through virtual space.

Immersion has continued its efforts to bring haptics to the mainstream consumer by developing a haptically enabled mouse that allows users to touch graphical user interfaces. Granted, force-feedback mice aren`t new; since 1993, Haptic Technologies has marketed a MouseCAT system, now priced at $2900 (in-cluding software), focused on improving computer accessibility for the blind. But Immersion`s Feelit Mouse will be significantly less expensive at $129 when it ships in the second quarter of 1999. With this mouse, computer users will be able to experience tactile sensations in two dimensions when they move across the icons, buttons, sliders, and borders of a computer interface as well as when they adjust the size of windows, trash files, or folders, says Immersion president Louis Rosenberg. The Feelit Mouse will also be able to sense haptic features inserted into commercial software products and Web sites.

Rosenberg believes the addition of "feel" to general computing will improve users` ability to find targets on the screen and execute commands. "The whole notion of taking the cursor and putting it on a target is a hard task," he says. "In the computer world today, people are impaired." Case in point: At a recent Comdex show, Immersion employees asked approximately 1000 visitors to connect a series of dots on a computer monitor with conventional and Feelit mice. When the test subjects used the Feelit Mouse, they reached their targets 88% faster and made half as many errors, he says.

Professional Applications

Two recent developments have increased the likelihood of new markets for professional haptics applications that provide more sophisticated simulations of touch. First, companies have improved their system software so their products are easier to use. "This has been the biggest accelerator in the market in the past year," says SensAble president Bill Aulet. "Our sales have increased fivefold, and we have now shipped hundreds of units due to the arrival and maturing of the Ghost software-development environment." Second, system costs have continued to drop. SensAble, for example, announced this summer a new PHANToM Desktop system costing just under $10,000--half the price of its previous product line. Also, Haptic Technologies unveiled plans to introduce a simpler pen-based device called the PenCAT/Pro for $679 in the first quarter of next year.

The application attracting industry watchers` most fervent interest is computer-aided engineering, where the potential for cost savings looms large. Automotive and aircraft manufacturers spend a great deal of money and time during product development to create physical models for design evaluation in body styling, ergonomics assessment, and parts assemblies. Each of these functions relies heavily on tactile feedback, so haptic CAD packages could eliminate the need for at least some physical modeling, thereby boosting productivity. In its company research where touch was used in CAD applications, modeling errors were reduced by a third, says Haptic Technol-ogies president Matthew Mather.

"Industrial use of haptics-based CAD is just beginning, but it`s real," says professor Blake Hannaford, director of the University of Washington`s Biorobotics Laboratory. Ironically, the rise of 3D visualization appears to be one of the driving forces behind the move to using force feedback within the engineering community. "One of the big problems with 3D in CAD is that it`s hard to see where the cursor is on the screen," explains Chuck Jacobus, president of Cybernet Systems. "Sculpting and constructing 3D shapes are inefficient and nonproductive."

Researchers in major automotive and aerospace companies already are looking for practical ways to adapt haptics technology to improve quality and reduce costs in product development. Boeing, for example, is developing simulations that demonstrate how force feedback can be used in CAD analysis and factory-floor training. Bill McNeely, an associate technical fellow in Applied Research and Technology at Boeing, says the firm wants to use haptics for evaluating maintenance access and test-assembly sequences during product design. The demonstration system will include a handle, attached to the end of a haptic device, that engineers can grasp and move along a particular pathway in the product simulation. Also, Boeing has developed software called VoxMap Pointshell that generates forces over all six directions of motion for that system`s rigid body manipulator. By midyear 1999, McNeely expects the CAD system to provide "very compelling demonstrations" of maintenance-access analysis.

Although haptic CAD packages aren`t available yet, such offerings appear to be just around the corner. This summer Haptics Technologies announced a late-1998 release date for a software "bridge" that imports models with touch features into software packages that use Spatial Technology`s (Boulder, CO) popular ACIS modeling kernel. Also, SensAble Technologies is engaged in serious discussions with software makers interested in integrating their products with PHANToM, says Aulet.

Another professional application often cited for haptics technology is CG animation, where artists now use cumbersome mice to create sophisticated 3D effects. Last May, Interactive Effects (Tustin, CA), announced that it has integrated SensAble`s 3D Touch System with its Amazon 3D Paint 3.0 package, a product used extensively on SGI machines in the film industry to paint 3D models. With a force-feedback version of the paint program, artists can use a hand-held stylus that functions like a brush, applying virtual paint on 3D objects. According to company president Tom Benoist, haptic forces sent through the stylus give artists enough tactile feedback to make their brushes flare or feather with slight changes in pressure. The user can rotate this virtual brush freely, sensing surface textures as well as the thickness of the virtual paint.

According to Tom Cushwa, a New York illustrator/animator who uses Amazon 3D Paint, the software`s new force-feedback option still needs refinement, but it has already proven particularly helpful in enhancing the sensitivity of airbrushing. Haptics technology`s most promising application, he predicts, will come in the area of 3D modeling, where the ability to work with a virtual surface--as if it were made out of clay--could provide the artist with a level of dexterity not currently possible with a mouse.

In chemistry research, commercial applications of haptics technology also show promise for dissolving barriers between scientists and their models. Interactive Simulations of San Diego, California, is marketing software that lets researchers and students directly manipulate virtual molecules. Instead of using a keyboard or mouse, the user grasps the model by pressing the button on a stylus. By moving the stylus, the user can feel attractive or repulsive forces acting on the molecule. The interface works so well, claims Len Wagner, Interactive Simulations` director of product development, that in formal user studies at the University of North Carolina, molecular modelers performed their work twice as fast and with a slight in-crease in accuracy.

On the high end of the professional haptics market is training simulation, where the reliance on virtual reality makes the need for touch even more important. A lot of early development in this area has focused on surgical education. Medical students learn their craft by first observing experienced surgeons and then performing procedures of gradually increasing skill. But if they performed some of their work on surgical simulators, they could gain experience more rapidly and practice unusual or complex operations earlier and more often in their training. Also, their work on the simulators could be recorded, providing some quantitative measure of the user`s skill.

Boston Dynamics Inc. (BDI), one of the early entrants in the medical-simulation field, is commercializing surgical simulators with haptic interfaces for arthroscopy of the knee, anastomosis (suturing of tube-like organs), and treatment of limb trauma by Army medical personnel. Trainees using this system stand in the same position as they would during surgery, looking down at a reflected 3D visualization of a particular body region. They also hold instruments whose movements are shadowed by replicas in the CG scene. As the students use these surgical tools, they feel a physically realistic response from the tissues they cut and stitch. To augment the experience, the system measures and displays students` scores for a variety of performance parameters, says Robert Playter, BDI`s vice president of engineering. This system includes two PHANToM haptic interfaces and a PC for running the simulator. A variety of Silicon Graphics workstations can be used to display the graphics; for the SGI Octane option, the approximate cost of the setup is $175,000.

For the medical establishment to accept simulation, however, it must deliver better training in less time at a lower cost. BDI`s anastomosis simulator is being evaluated at Penn State University`s Hershey Medical Center, where all incoming surgery residents and attending surgeons are using the system along with its performance-measurement feature. The goal of the equipment evaluation is to determine whether the simulator can differentiate various levels of expertise and if it helps students improve their skills. "We can say that incoming surgical residents perform better after several episodes," says Paul Gorman, general-surgery resident, "but further validation is required."

Manufacturers also see force feedback as an essential complement to visualization in computer-based job-training systems, but not all of these applications require the same degree of sophistication as surgery. At Boeing, McNeely`s group is developing a demonstration simulator in which trainees would learn to "drill straight holes" for aircraft rivets. The simulation would allow workers to hold a drill and feel haptic forces as they penetrate the outer skin of a surface panel. But for this task, Boeing needs a haptic simulator that can generate substantial force. So it is turning to Haptic Technologies Inc., a Seattle, Washington, start-up that is providing a four-degrees-of-freedom system which is expected to be ready for demonstration by year-end.

Adaptive devices for the disabled comprise another application area for force feedback. Haptic Technologies of Montreal has developed a touch mouse that translates icons and buttons on a Windows interface for the blind. In addition, the CyberTouch option of Virtual Technologies` CyberGlove can be adapted so that words typed into a keypad can be displayed as tactile signals to a deaf or deaf/blind person wearing the glove.

Researchers are also demonstrating the potential of force feedback to enhance and evaluate musical performance. While at Stanford`s Center for Computer Research in Music and Acoustics (CCRMA), Brent Gillespie, a Northwestern University postdoctoral researcher, built a motorized keyboard that produces piano-like tactile vibrations when played. As a classically trained pianist, Gillespie knows that musical instruments vibrate in ways that deliver valuable feedback to the musician, and he is hoping that haptics can make it easier for people to learn to play electronic instruments such as synthesizers.

At CCRMA, researcher Sile O`Modhrain is working on a haptic interface that would serve as a tool for comparing different musical performances. Her approach presents subtle nuances in musical renderings as modulations in the stiffness of a virtual surface, which are presented to the user through a prototype force-feedback device called the Moose. A sound engineer could make use of such small details, which are not immediately apparent from the graphical representations of sound data now standard in audio-editing applications, she adds.

Developments on the Horizon

While force-feedback products are finding niches in the commercial marketplace, technical limitations still remain. For instance, today`s haptic interfaces provide only a bare approximation of a human`s sensitivity for touch. In distinguishing between today`s force-feedback devices and the tactile feedback interfaces needed to make virtual objects feel authentic, Harvard professor Robert Howe says the former are "like poking at the world with a stick," while the latter promise to provide the distributed sensations across the skin needed for realistic simulations of touch. In addition, force-feedback systems only have to represent motion over three degrees of freedom, while tactile arrays provide touch information in many dimensions. In his laboratory, Howe and his students are developing tactile displays whose arrays of pins rise and fall under computer control, transmitting an object`s tactile qualities to a human user by conveying a blend of physical impressions, including high-frequency vibrations and small-scale shape or pressure distributions.

Another problem with current systems is that, like all mechanical devices, they are prone to performance limitations resulting from system friction, inertia, and instability. Carnegie Mellon University professor Ralph Hollis` solution is an interface consisting of a single lightweight component that floats in a magnetic field, in which force feedback is generated by electric currents. By holding a knob-like handle, users can touch and turn objects within a full six degrees of freedom, and according to Hollis, the interface`s 1-inch motion range is adequate for most applications. He and his colleagues are now looking for the best way to integrate the fast response of this magnetic-levitation device with the relatively slow graphics-update rate of current workstation-based modeling environments.

No single device configuration is likely to meet all needs, so standards governing such specifications as acceptable interfaces and control methods need to be agreed on, says the University of Washington`s Hannaford. Without these rules of the road, he explains, software developers cannot be assured that their applications will operate the same way on all interfacing devices.

In the past few years, most of the focus of commercial haptics development has been to improve interfaces; however, the industry is paying increasingly close attention to the software-engineering challenges of the technology. Hannaford says haptic models require much more computing power than computer-graphics programs, making them difficult to integrate into existing code for computer-graphics software. But Dinesh Pai, a professor of computer science at the University of British Columbia, foresees a reduction in the time needed to process tactile sensations, thanks to research aimed at developing better algorithms for extremely fast collision detection. Another effective way to save computing time might be to convey a desired tactile impression without developing a high-fidelity model. To this end, Pai and his colleagues have studied the effectiveness of sound cues in reinforcing the message conveyed by a touch impression. They have found that realistic sounds of haptic interaction can be easily synthesized, enabling them to convey many haptic perceptions such as hardness, material, texture, and shape.

An additional software-engineering problem rests with the need for force-feedback content-haptic features that can be imported into existing software packages. Al-though Pai cautions that it will be much more difficult to develop substantive content for touch than for CG applications, a solution, he believes, is on the horizon. "You`ve seen the revolution in 3D scanning and motion tracking for modeling and animation. The same kinds of things can be done with haptics to build up libraries of objects," he says. Working toward that goal, Pai and his colleagues have built an Active Measurement Facility that allows them to automate the generation of multisensory models with visual, auditory, and haptic features. These models could be added to libraries that are easily imported into design applications.

Like other observers, Pai sees a need for standards that will allow different kinds of interfaces to be compatible with all haptic models; however, he thinks it will be difficult to design such specifications in today`s fluid development environment. "My guess is that it may be another year or so before it becomes clear what the core functionality of haptic interaction is," he says. "Every haptic device comes with its own specialized software-development kit, but as they evolve, I think some common ideas will evolve into a VRML extension."

With so many unanswered questions about hardware and software, it`s no surprise that comparatively little attention has been paid to the capabilities and limitations of the human operators of these haptic technologies. Susan Lederman, a professor of psychology and computing and information sciences at Queen`s University in Kingston, Ontario, believes that researchers must develop a clearer view of what tasks each of the human senses (sight, hearing, and touch) do best and how they may interact most effectively in multimodal computer displays. "Your sense of sight has very high spatial resolution and picks up very fine spatial details both quickly and accurately, while touch cannot perform at that same high level," she says.

On the other hand, the sense of touch excels at identifying material properties of objects, such as their surface texture and compliancy. To illustrate this claim, Lederman points to a study she conducted in which people could easily identify a screwdriver by touch but struggled to recognize a raised outline depiction of it. Test subjects couldn`t use their sense of sight effectively to perform this task, she believes, because they lacked relevant information for the haptic system about the screwdriver`s surface textures, hardness, and thermal conductivity. "The only information available was contained in the raised contours, which people could only extract slowly over time, bit by bit, and then reassemble in their minds," says Lederman, who collaborates with Roberta Klatzky, a professor of psychology at Carnegie Mellon University. "It is not surprising, then, that such spatial information is processed more effectively by vision than by the haptic system."

In using multimodal displays, designers will need to understand how humans respond to the information accessible to different senses, according to Lederman. Her research has shown that there may be no advantage to reinforcing a design message with two senses when one of them is the dominant means used to gather particular information. She also cautions that designers injecting touch into computer applications, such as CAD systems, may need to take more than human sensory and perceptual capabilities into account. For example, they will also likely need to understand the impact of human-cognitive processes in interpreting force-feedback displays. "The knowledge, training, and experience the human operator brings to the haptic application could facilitate or interfere with the effective use of these systems," she says. "Little has been done to investigate these areas as yet."

A Fundamental Change in Computing

Much work remains in improving haptics systems and devising design principles for effective touch interfaces, but the technology still appears to be crossing the threshold of commercial viability. Some of this growth stems from the ability to satisfy curiosity with low-cost applications like gaming and tactile computer desktops. Another part reflects a conviction that the ability to feel--even with rudimentary sensitivity--is ready to improve work tasks such as CAD, CAE, animation, and surgical training. Yet another reason for this increased interest in haptics is the simple belief that the technology represents the next step in expanding the computer`s basic capabilities as a learning tool.

At this year`s SIGGRAPH conference and exhibition, visitors showed much more interest in force feedback than ever, according to representatives from haptics companies. "People are just beginning to realize the value of the technology," says James Kramer, president of Virtual Technologies. "Haptics is the missing component for multimedia."

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Immersion helped push haptics into the mainstream market by offering products based on its I-Force technology. For instance, the company`s Force-RS force-feedback racing wheel for home gaming offers users arcade-quality performance for less than $200.

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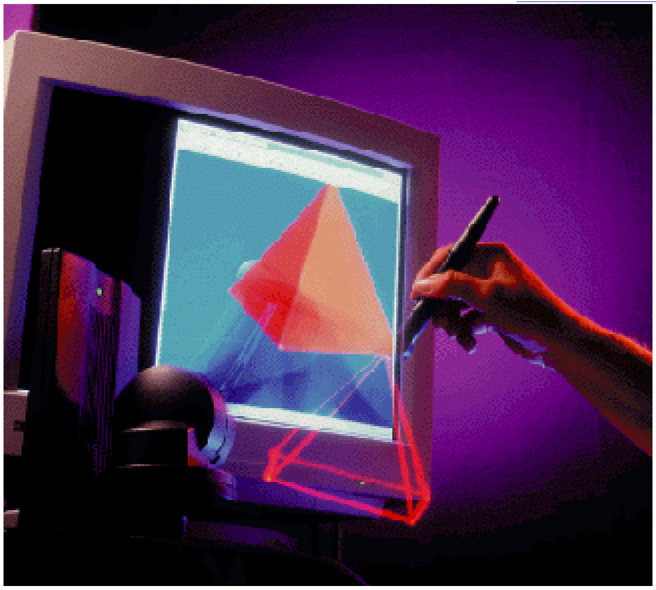

SensAble has added 3D Touch force-feedback technology to its PHANToM architecture, opening up a range of applications, including digital prototyping, which enables users to touch and manipulate objects.

Users can simulate grasping-based applications with Virtual Technologies` CyberGrasp force-feedback option for its CyberGlove.

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Scheduled to ship in mid-1999, Immersion?s $129 Feelit Mouse will provide high-fidelity feedback in gaming, business, and Web applications.

Haptic Technologies? 3D pen with force feedback enables CAD designers, animators, and 3D modelers to OfeelO curves, edges, and surface textures of objects they are designing on the computer screen.

Medical students can get a real feel for surgical techniques using Boston Dynamics` surgical simulator. Holding surgical instruments, the trainees receive a physically realistic response as they simulate the cutting and suturing of tissue.

SensAble`s 3D Touch technology provides a new, more innovative and artistic approach to organic 3D modeling.

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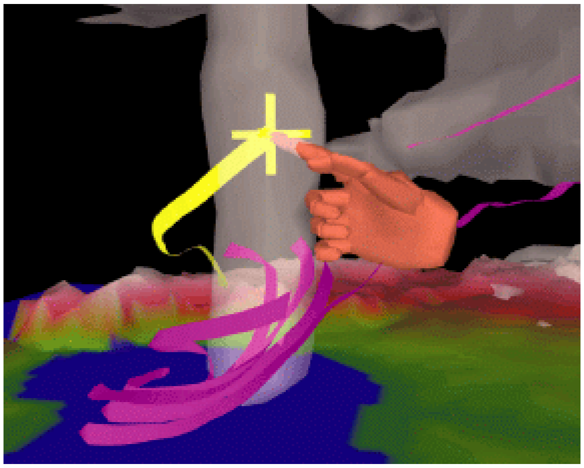
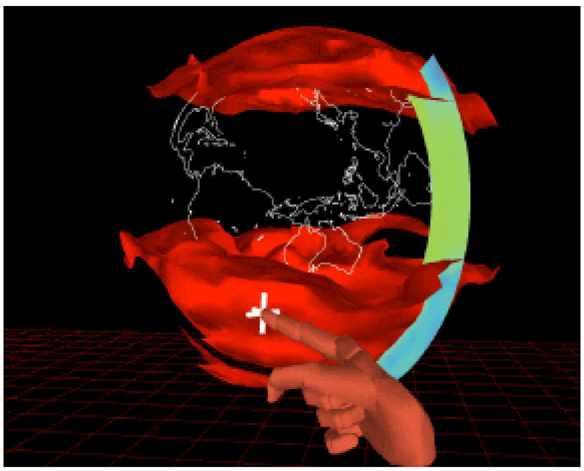
This $150 high-performance force-feedback joystick from Immersion uses the same high-fidelity cable-driven technology the firm used to sell to research labs for $5000.



Researchers at NASA`s Goddard Space Flight Center are using Virtual Technologies` CyberGlove to interact with a variety of simulations, including a hurricane visualization.



Researchers at NASA`s Goddard Space Flight Center are using Virtual Technologies` CyberGlove to interact with a variety of simulations, including a global methane-distribution simulation.

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Computer Graphics World October, 1998