CHAPTER 1

Introduction to Haptics

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Haptics refers to the modality of touch and associated sensory feedback. Researchers working in the area are concerned with the development, testing, and refinement of tactile and force feedback devices and supporting software that permit users to sense ("feel") and manipulate three-dimensional virtual objects with respect to such features as shape, weight, surface textures, and temperature. In addition to basic psychophysical research on human haptics, and issues in machine haptics such as collision detection, force feedback, and haptic data compression, work is being done in application areas such as surgical simulation, medical training, scientific visualization, and assistive technology for the blind and visually impaired.

How can a device emulate the sense of touch? Let us consider one of the devices from SensAble Technologies. The 3 DOF (degrees-of-freedom) PHANToM is a small robot arm with three revolute joints, each connected to a computer-controlled electric DC motor. The tip of the device is attached to a stylus that is held by the user. By sending appropriate volt-

ages to the motors, it is possible to exert up to 1.5 pounds of force at the tip of the stylus, in any direction.

The basic principle behind haptic rendering is simple: Every millisecond or so, the computer that controls the PHANToM reads the joint encoders to determine the precise position of the stylus. It then compares this position to those of the virtual objects the user is trying to touch. If the user is away from all the virtual objects, a zero voltage is sent to the motors and the user is free to move the stylus (as if exploring empty space). However, if the system detects a collision between the stylus and one of the virtual objects, it drives the motors so as to exert on the user's hand (through the stylus) a force along the exterior normal to the surface being penetrated. In practice, the user is prevented from penetrating the virtual object *just as if the stylus collided with a real object that transmits a reaction to the user's hand*. Different haptic devices—such as Immersion Corporation's CyberGrasp—operate under the same principle but with different mechanical actuation systems for force generation.

Although the basic principles behind haptics are simple, there are significant technical challenges, such as the construction of the physical devices (cf. Chapter 4), real-time collision detection (cf. Chapters 2 and 5), simulation of complex mechanical systems for precise computation of the reaction forces (cf. Chapter 2), and force control (cf. Chapters 3 and 5). Below we provide an overview of haptics research; we consider *haptic devices*, *applications*, *haptic rendering*, and *human factors* issues.

HAPTIC DEVICES

Researchers have been interested in the potential of force feedback devices such as stylus-based masters like SensAble's PHANToM (Salisbury, Brock, Massie, Swarup, & Zilles, 1995; Salisbury & Massie, 1994) as alternative or supplemental input devices to the mouse, keyboard, or joystick. As discussed above, the PHANToM is a small, desk-grounded robot that permits simulation of single fingertip contact with virtual objects through a thimble or stylus. It tracks the x, y, and z Cartesian coordinates and pitch, roll, and yaw of the virtual probe as it moves about a three-dimensional workspace, and its actuators communicate forces back to the user's fingertips as it detects collisions with virtual objects, simulating the sense of touch. The CyberGrasp, from Immersion Corporation, is an exoskeletal device that fits over a 22 DOF CyberGlove, providing force feedback. The CyberGrasp is used in conjunction with a position tracker to measure the position and orientation of the forearm in three-dimensional space. (A newly released model of the CyberGrasp is self-contained and does not require an external tracker.) Similar to the CyberGrasp is the Rutgers Master II (Burdea, 1996; Gomez, 1998; Langrana, Burdea, Ladeiji, & Dinsmore, 1997), which has an actuator platform mounted on the palm that gives force feedback to four fingers. Position tracking is done by the Polhmeus Fastrak.

Alternative approaches to haptic sensing have employed vibrotactile display, which applies multiple small force vectors to the fingertip. For example, Ikei, Wakamatsu, and Fu-

kuda (1997) used photographs of objects and a contact pin array to transmit tactile sensations of the surface of objects. Each pin in the array vibrates commensurate with the local intensity (brightness) of the surface area, with image intensity roughly correlated with the height of texture protrusions. There is currently a joint effort underway at MIT and Carnegie Mellon (Srinivasan, 2001) to explore the incorporation of microelectromechanical systems (MEMS) actuator arrays into haptic devices and wearables. Researchers at the University of Wisconsin are experimenting with tactile strips containing an array of sensors that can be attached to various kinds of force-feedback devices (Tyler, 2001). Howe (1994) notes that vibrations are particularly helpful in certain kinds of sensing tasks, such as assessing surface roughness or detecting system events (for example, contact and slip in manipulation control).

Researchers at the Fraunhofer Institute for Computer Graphics in Darmstadt have developed a glove-like device they call the ThermoPad, a haptic temperature display based on Peltier elements and simple heat transfer models. They are able to simulate not only the "environmental" temperature but also the sensation of heat or cold one experiences when grasping or colliding with an object. At the University of Tsukuba in Japan, Iwata, Yano, and Hashimoto (1997) are using the HapticMaster, a 6 DOF device with a ball grip that can be replaced by various real tools for surgical simulations and other specialized applications. A novel type of haptic display is the Haptic Screen (Iwata, Yano, and Hashimoto, 1997), a device with a rubberized elastic surface with actuators, each with force sensors, underneath. The surface of the Haptic Screen can be deformed with the naked hand. An electromagnetic interface couples the ISU Force Reflecting Exoskeleton (Luecke & Chai, 1997), developed at Iowa State University, to the operator's two fingers, eliminating the burdensome heaviness usually associated with exoskeletal devices. Researchers at the University of California, Berkeley (Chapter 4, this volume) developed a high performance 3 DOF hand-scale haptic interface. Their device exhibits high stiffness due to a 10-link design with three closed kinematic loops and a direct-drive mechanical system that avoids transmission elements.

Finally, there is considerable interest in 2D haptic devices. For example, Pai and Reissell at the University of British Columbia have used the Pantograph 2D haptic interface, a two-DOF force-feedback planar device with a handle the user moves like a mouse, to feel the edges of shapes in images (Pai & Reissell, 1997). A new 2D haptic mouse from Immersion Corporation is based on optical technology and is free-moving rather than tethered to a base. Other 2D devices, like the Moose, Sidewinder, and the Wingman mouse, are described below in the section on "Assistive Technology for the Blind and Visually Impaired."

REPRESENTATIVE APPLICATIONS OF HAPTICS

Surgical Simulation and Medical Training

A primary application area for haptics has been in surgical simulation and medical training. Langrana, Burdea, Ladeiji, and Dinsmore (1997) used the Rutgers Master II haptic

device in a training simulation for palpation of subsurface liver tumors. They modeled tumors as comparatively harder spheres within larger and softer spheres. Realistic reaction forces were returned to the user as the virtual hand encountered the "tumors," and the graphical display showed corresponding tissue deformation produced by the palpation. Finite Element Analysis was used to calculate the reaction forces corresponding to deformation from experimentally obtained force/deflection curves. Researchers at the Universidade Catolica de Brasilia-Brasil (D'Aulignac & Balaniuk, 1999) have produced a physical simulation system providing graphic and haptic interfaces for an echographic examination of the human thigh, using a spring damper model defined from experimental data. Machaco, Moraes and Zuffo (2000) have used haptics in an immersive simulator of bone marrow harvest for transplant. Andrew Mor of the Robotics Institute at Carnegie Mellon (Mor, 1998) employed the PHANToM in conjunction with a 2 DOF planar device in an arthroscopic surgery simulation. The new device generates a moment measured about the tip of a surgical tool, thus providing more realistic training for the kinds of unintentional contacts with ligaments and fibrous membranes that an inexperienced resident might encounter. At Stanford, Balaniuk and Costa (2000) have developed a method to simulate fluid-filled objects suitable for interactive deformation by "cutting," "suturing," and so on. At MIT, De and Srinivasan (1998) have developed models and algorithms for reducing the computational load required to generate visual rendering of organ motion and deformation and the communication of forces back to the user resulting from tool-tissue contact. They model soft tissue as thin-walled membranes filled with fluid. Force-displacement response is comparable to that obtained in *in vivo* experiments. At Berkeley, Sastry and his colleagues (Chapter 13, this volume) are engaged in a joint project with the surgery department of the University of California at San Francisco and the Endorobotics Corporation to build dexterous robots for use inside laparoscopic and endoscopic cannulas, as well as tactile sensing and teletactile display devices and masters for surgical teleoperation (2001). Aviles and Ranta of Novint Technologies have developed the Virtual Reality Dental Training System dental simulator (Aviles & Ranta, 1999). They employ a PHANToM with four tips that mimic dental instruments; they can be used to explore simulated materials like hard tooth enamel or dentin. Giess, Evers, and Meinzer (1998) integrated haptic volume rendering with the PHANToM into the presurgical process of classifying liver parenchyma, vessel trees, and tumors. Surgeons at the Pennsylvania State University School of Medicine, in collaboration with Cambridge-based Boston Dynamics, used two PHANToMs in a training simulation in which residents passed simulated needles through blood vessels, allowing them to collect baseline data on the surgical skill of new trainees. Iwata, Yano, and Hashimoto (1998) report the development of a surgical simulator with a "free form tissue" which can be "cut" like real tissue. There are few accounts of any systematic testing and evaluation of the simulators described above. Gruener (1998), in one of the few research reports with hard data, expresses reservations about the potential of haptics in medical applications; he found that subjects in a telementoring session did not profit from the addition of force feedback to remote ultrasound diagnosis.

Museum Display

Although it is not yet commonplace, a few museums are exploring methods for 3D digitization of priceless artifacts and objects from their sculpture and decorative arts collections, making the images available via CD-ROM or in-house kiosks. For example, the Canadian Museum of Civilization collaborated with Ontario-based Hymarc to use the latter's ColorScan 3D laser camera to create three-dimensional models of objects from the museum's collection (Canarie, Inc., 1998; Shulman, 1998). A similar partnership was formed between the Smithsonian Institution and Synthonic Technologies, a Los Angeles-area company. At Florida State University, the Department of Classics has worked with a team to digitize Etruscan artifacts using the RealScan 3D imaging system from Real 3D (Orlando, Florida), and art historians from Temple University have collaborated with researchers from the Watson Research Laboratory's visual and geometric computing group to create a model of Michaelangelo's *Pieta*, using the Virtuoso shape camera from Visual Interface (Shulman, 1998).

Few museums have yet explored the potential of haptics to allow visitors access to three-dimensional museum objects such as sculpture, bronzes, or examples from the decorative arts. The "hands-off" policies that museums must impose limit appreciation of three-dimensional objects, where full comprehension and understanding rely on the sense of touch as well as vision. Haptic interfaces can allow fuller appreciation of three-dimensional objects without jeopardizing conservation standards, giving museums, research institutes, and other conservators of priceless objects a way to provide the public with a vehicle for object exploration in a modality that could not otherwise be permitted (McLaughlin, Goldberg, Ellison, & Lucas, 1999). At the University of Southern California, researchers at the Integrated Media Systems Center (IMSC) have digitized daguerreotype cases from the collection of the Seaver Center for Western Culture at the Natural History Museum of Los Angeles County and made them available at a PHANToM-equipped kiosk alongside an exhibition of the "real" objects (see Chapter 15, this volume). Bergamasco, Jannson and colleagues (Jansson, 2001) are undertaking a "Museum of Pure Form"; their group will acquire selected sculptures from the collections of partner museums in a network of European cultural institutions to create a digital database of works of art for haptic exploration.

Haptics raises the prospect of offering museum visitors not only the opportunity to examine and manipulate digitized three-dimensional art objects visually, but also to interact remotely, in real time, with museum staff members to engage in joint tactile exploration of the works of art such that someone from the museum's curatorial staff can interact with a student in a remote classroom and together they can jointly examine an ancient pot or bronze figure, note its interesting contours and textures, and consider such questions as "What is the mark at the base of the pot?" or "Why does this side have such jagged edges?" (Hespanha, Sukhatme, McLaughlin, Akbarian, Garg, & Zhu, 2000; McLaughlin, Sukhatme, Hespanha, Shahabi, Ortega, & Medioni, 2000; Sukhatme, Hespanha, McLaughlin, Shahabi, & Ortega, 2000).

Painting, Sculpting, and CAD

There have been a few projects in which haptic displays are used as alternative input devices for painting, sculpting, and computer-assisted design (CAD). Dillon and colleagues (Dillon, Moody, Bartlett, Scully, Morgan, & James, 2000) are developing a "fabric language" to analyze the tactile properties of fabrics as an information resource for haptic fabric sensing. At CERTEC, the Center of Rehabilitation Engineering in Lund, Sweden, Sjostrom (Sjostrom, 1997) and his colleagues have created a painting application in which the PHANToM can be used by the visually impaired; line thickness varies with the user's force on the fingertip thimble and colors are discriminated by their tactual profile. At Dartmouth, Henle and Donald (1999) developed an application in which animations are treated as palpable vector fields that can be edited by manipulation with the PHANToM. Marcy, Temkin, Gorman, and Krummel (1998) have developed the Tactile Max, a PHANToM plug-in for 3D Studio Max. *Dynasculpt,* a prototype from Interval Research Corporation (Snibbe, Anderson, & Verplank, 1998) permits sculpting in three dimensions by attaching a virtual mass to the PHANToM position and constructing a ribbon through the path of the mass through the 3D space. Gutierrez, Barbero, Aizpitarte, Carrillo, and Eguidazu (1998) have integrated the PHANToM into DATum, a geometric modeler. Objects can be touched, moved, or grasped (with two PHANToMs), and the assembly/disassembly of mechanical objects can be simulated.

Visualization

Haptics has also been incorporated into scientific visualization. Durbeck, Macias, Weinstein, Johnson, and Hollerbach (1998) have interfaced SCIrun, a computation software steering system, to the PHANToM. Both haptics and graphics displays are directed by the movement of the PHANToM stylus through haptically rendered data volumes. Similar systems have been developed for geoscientific applications (e.g., the Haptic Workbench, Veldkamp, Truner, Gunn, and Stevenson, 1998). Green and Salisbury (1998) have produced a convincing soil simulation in which they have varied parameters such as soil properties, plow blade geometry, and angle of attack. Researchers at West Virginia University (Van Scoy, Baker, Gingold, Martino, & Burton, 1999) have applied haptics to mobility training. They designed an application in which a real city block and its buildings could be explored with the PHANToM, using models of the buildings created in CANOMA from digital photographs of the scene from the streets. At Interactive Simulations, a San Diego-based company, researchers have added a haptic feedback component to *Sculpt,* a program for analyzing chemical and biological molecular structures, which will permit analysis of molecular conformational flexibility and interactive docking. At the University of North Carolina, Chapel Hill (Chapter 5, this volume), 6 DOF PHANToMs have been used for haptic rendering of high-dimensional scientific datasets, including three-dimensional force fields and tetrahedralized human head volume datasets. We consider further applications of haptics to

visualization below, in the section "Assistive Technology for the Blind and Visually Impaired."

Military Applications

Haptics has also been used in aerospace and military training and simulations. There are a number of circumstances in a military context in which haptics can provide a useful substitute information source; that is, there are circumstances in which the modality of touch could convey information that for one reason or another is not available, not reliably communicated, nor even best apprehended through the modalities of sound and vision. In some cases, combatants may have their view blocked or may not be able to divert attention from a display to attend to other information sources. Battlefield conditions, such as the presence of artillery fire or smoke, might make it difficult to hear or see. Conditions might necessitate that communications be inaudible (Transdimension, 2000). For certain applications, for example where terrain or texture information needs to be conveyed, haptics may be the most efficient communication channel. In circumstances like those described above, haptics is an *alternative* modality to sound and vision that can be exploited to provide low-bandwidth situation information, commands, and threat warning (Transdimension, 2000). In other circumstances haptics could function as a *supplemental* information source to sound or vision. For example, users can be alerted haptically to interesting portions of a military simulation, learning quickly and intuitively about objects, their motions, what persons may interact with them, and so on.

At the Army's National Automotive Center, the SimTLC (Simulation Throughout the Life Cycle) program has used VR techniques to test military ground vehicles under simulated battlefield conditions. One of the applications has been a simulation of a distributed environment where workers at remote locations can collaborate in reconfiguring a single vehicle chassis with different weapons components, using instrumented force-feedback gloves to manipulate the three-dimensional components (National Automotive Center, 1999). The SIRE simulator (Synthesized Immersion Research Environment) at the Air Force Research Laboratory, Wright-Patterson Air Force Base, incorporated data gloves and tactile displays into its program of development and testing of crew station technologies (Wright-Patterson Air Force Base, 1997). Using tasks such as mechanical assembly, researchers at NASA-Ames have been conducting psychophysical studies of the effects of adding a 3 DOF force-feedback manipulandum to a visual display, noting that control and system dynamics have received ample research attention but that the human factors underlying successful haptic display in simulated environments remain to be identified (Ellis & Adelstein, n.d.). The Naval Aerospace Medical Research Laboratory has developed a "Tactile Situation Awareness System" for providing accurate orientation information in land, sea, and aerospace environments. One application of the system is to alleviate problems related to the spatial disorientation that occurs when a pilot incorrectly perceives the attitude, altitude, or motion of his aircraft; some of this error may be attributable to momentary distraction, reduced visibility, or an increased workload. Because the system (a vibrotactile transducer) can be attached to a portable sensor, it can also be used in such applications as extravehicular space exploration

activity or Special Forces operations. Among the benefits claimed for integration of haptics with audio and visual displays are increased situation awareness, the ability to track targets and information sources spatially, and silent communication under conditions where sound is not possible or desirable (e.g., hostile environments) (Naval Aerospace Medical Research Laboratory, 2000).

Interaction Techniques

An obvious application of haptics is to the user interface, in particular its repertoire of *interaction techniques*, loosely considered that set of procedures by which basic tasks, such as opening and closing windows, scrolling, and selecting from a menu, are performed (Kirkpatrick & Douglas, 1999). Indeed, interaction techniques have been a popular application area for 2D haptic mice like the Wingman and I-Feel, which work with the Windows interface to add force feedback to windows, scroll bars, and the like. For some of these force-feedback mice, shapes, textures, and other properties of objects (spring, damping) can be "rendered" with Javascript and the objects delivered for exploration with the haptic mice via standard Web pages. Haptics offers a natural user interface based on the human gestural system. The resistance and friction provided by stylus-based force feedback adds an intuitive feel to such everyday tasks as dragging, sliding levers, and depressing buttons. There are more complex operations, such as concatenating or editing, for which a grasping metaphor may be appropriate. Here the whole-hand force feedback provided by glove-based devices could convey the feeling of stacking or juxtaposing several objects or of plucking an unwanted element from a single object. The inclusion of palpable physics in virtual environments, such as the constraints imposed by walls or the effect of altered gravity on weight, may enhance the success of a user's interaction with the environment (Adelstein & Ellis, 2000).

Sometimes too much freedom to move is inefficient and has users going down wrong paths and making unnecessary errors that system designers could help them avoid by the appropriate use of built-in force constraints that encourage or require the user to do things in the "right" way (Hutchins & Gunn, 1999). Haptics can also be used to constrain the user's interaction with screen elements, for example, by steering him or her away from unproductive areas for the performance of specific tasks, or making it more difficult to trigger procedures accidentally by increasing the stiffness of the controls.

Assistive Technology for the Blind and Visually Impaired

Most haptic systems still rely heavily on a combined visual/haptic interface. This dual modality is very forgiving in terms of the quality of the haptic rendering. This is because ordinarily the user is able to see the object being touched and naturally persuades herself that the force feedback coming from the haptic device closely matches the visual input. However, in most current haptic interfaces, the quality of haptic rendering is actually poor and, if the

user closes her eyes, she will only be able to distinguish between very simple shapes (such as balls, cubes, etc.).

To date there has been a modest amount of work on the use of machine haptics for the blind and visually impaired. Among the two-dimensional haptic devices potentially useful in this context, the most recent are the Moose, the Wingman, the I-Feel, and the Sidewinder. The Moose, a 2D haptic interface developed at Stanford (O'Modhrain & Gillespie, 1998), reinterprets a Windows screen with force feedback such that icons, scroll bars, and other screen elements like the edges of windows are rendered haptically, providing an alternative to the conventional graphical user interface (GUI). For example, drag-and-drop operations are realized by increasing or decreasing the apparent mass of the Moose's manipulandum. Although not designed specifically with blind users in mind, the Logitech Wingman, developed by Immersion Corporation and formerly known as the "FEELit" mouse, similarly renders the Windows screen haptically in two dimensions and works with the Web as well, allowing the user to "snap to" hyperlinks or feel the "texture" of a textile using a "FeeltheWeb" ActiveX control programmed through Javascript. (The Wingman mouse is now no longer commercially available). Swedish researchers have experimented, with mixed results, with two-dimensional haptic devices like the Microsoft Sidewinder joystick in games devised for the visually impaired, such as "Labyrinth," in which users negotiate a maze using force feedback (Johansson & Linde, 1998, 1999).

Among the three-dimensional haptic devices, Immersion's Impulse Engine 3000 has been shown to be an effective display system for blind users. Colwell et al. (1998) had blind and sighted subjects make magnitude estimations of the roughness of virtual textures using the Impulse Engine and found that the blind subjects were more discriminating with respect to the roughness of texture and had different mental maps of the location of the haptic probe relative to the virtual object than sighted users. The researchers found, however, that for complex virtual objects, such as models of sofas and chairs, haptic information was simply not sufficient to produce recognition and had to be supplemented with information from other sources for all users.

Most of the recent work in 3D haptics for the blind has tended to focus on SensAble's PHANToM. At CERTEC, the Center of Rehabilitation Engineering in Lund, Sweden, in addition to Sjöstrom's painting application, described earlier (Sjöstrom, 1997), a program has been developed for "feeling" mathematical curves and surfaces, and a variant of the game "Battleship" that uses force feedback to communicate the different sensations of the "water surface" as bombs are dropped and opponents are sunk. The game is one of the few that can also be enjoyed by deaf-blind children. Blind but hearing children may play "The Memory Game," a variation on "Concentration" based on sound-pair buttons that disappear tactually when a match is made (Rassmuss-Gröhn & Sjöstrom, 1998).

Jansson and his colleagues at Uppsala University in Sweden have been at the forefront of research on haptics for the blind (Jannson, 1998; Jansson & Billberger, 1999; Jansson, Faenger, Konig, & Billberger, 1998). Representive of this work is an experiment reported in Jansson and Billberger (1999), in which blindfolded subjects were evaluated for speed and accuracy in identifying virtual objects (cubes, spheres, cylinders, and cones) with the PHANToM and corresponding physical models of the virtual objects by hand exploration. Jansson

Jansson and Billberger found that both speed and accuracy in shape identification were significantly poorer for the virtual objects. Speed in particular was affected by virtue of the fact that the exploratory procedures most natural to shape identification, grasping and manipulating with both hands, could not be emulated by the single-point contact of the PHANToM tip. They also noted that subject performance was not affected by the type of PHANToM interface (thimble versus stylus). However, shape recognition of virtual objects with the PHANToM was significantly influenced by the size of the object, with larger objects being more readily identified. The authors noted that shape identification with the PHANToM is a considerably more difficult task than texture recognition, in that in the case of the latter a single lateral sweep of the tip in one direction may be sufficient, but more complex procedures are required to apprehend shape. In Chapter 9 of this volume Jansson reports on his work with nonrealistic haptic rendering and with the method of successive presentation of increasingly complex scenes for haptic perception when visual guidance is unavailable.

Multivis (Multimodal Visualization for Blind People) is a project currently being undertaken at the University of Glasgow, which will utilize force feedback, 3D sound rendering, braille, and speech input and output to provide blind users access to complex visual displays. Yu, Ramloll, and Brewster (2000) have developed a multimodal approach to providing blind users access to complex graphical data such as line graphs and bar charts. Among their techniques are the use of "haptic gridlines" to help users locate data values on the graphs. Different lines are distinguished by applying two levels of surface friction to them ("sticky" or "slippery"). Because these features have not been found to be uniformly helpful to blind users, a toggle feature was added so that the gridlines and surface friction could be turned on and off. Subjects in their studies had to use the PHANToM to estimate the x and y coordinates of the minimum and maximum points on two lines. Both blind and sighted subjects were effective at distinguishing lines by their surface friction. Gridlines, however, were sometimes confused with the other lines, and counting the gridlines from right and left margins was a tedious process prone to error. The authors recommended, based on their observations, that lines on a graph should be modeled as grooved rather than raised ("engraving" rather than "embossing"), as the PHANToM tip "slips off" the raised surface of the line.

Ramloll, Yu, and their colleagues (2000) note that previous work on alternatives to graphical visualization indicates that for blind persons, pitch is an effective indicator of the location of a point with respect to an axis. Spatial audio is used to assist the user in tasks such as detecting the current location of the PHANToM tip relative to the origin of a curve (Ramloll, Yu, et al., 2000). Pitches corresponding to the coordinates of the axes can be played in rapid succession to give an "overview" picture of the shape of the curve. Such global information is useful in gaining a quick overall orientation to the graph that purely local information can provide only slowly, over time. Ramloll et al. also recommend a guided haptic overview of the borders, axes, and curves—for example, at intersections of axes, applying a force in the current direction of motion along a curve to make sure that the user does not go off in the wrong direction.

Other researchers working in the area of joint haptic-sonification techniques for visualization for the blind include Grabowski and Barner (Grabowski, 1999; Grabowski & Barner, 1998). In this work, auditory feedback—physically modeled impact sound—is inte-

grated with the PHANToM interface. For instance, sound and haptics are integrated such that a virtual object will produce an appropriate sound when struck. The sound varies depending on such factors as the energy of the impact, its location, and the user's distance from the object (Grabowski, 1999).

ISSUES IN HAPTIC RENDERING

Acquisition of Models

There are several commercial 3D digitizing cameras available for acquiring models of objects, such as the ColorScan and the Virtuoso shape cameras mentioned earlier. The latter uses six digital cameras, five black and white cameras for capturing shape information and one color camera that acquires texture information that is layered onto the triangle mesh. At USC's IMSC one of the approaches to the digitization process begins with models acquired from photographs, using a semiautomatic system to infer complex 3-D shapes from photographs (Chen & Medioni, 1997, 1999, 2001). Images are used as the rendering primitives and multiple input pictures are allowed, taken from viewpoints with different position, orientation, and camera focal length. The direct output of the IMSC program is volumetric but is converted to a surface representation for the purpose of graphic rendering. The reconstructed surfaces are quite large, on the order of 40 MB. They are decimated with a modified version of a program for surface simplification using quadric error metrics written by Garland and Heckbert (1997). The LightScribe system (formerly known as the 3Scan system) incorporates stereo vision techniques developed at IMSC, and the process of matching points between images has been fully automated. Other comparable approaches to digitizing museum objects (e.g., Synthonics) use an older version of shape-from-stereo technology that requires the cameras to be calibrated whenever the focal length or relative position of the two cameras is changed.

Volumetric data is used extensively in medical imaging and scientific visualization. Currently the GHOST SDK, which is the development toolkit for the PHANToM, construes the haptic environment as scenes composed of geometric primitives. Huang, Qu, and Kaufman of SUNY-Stony Brook have developed a new interface that supports volume rendering, based on volumetric objects, with haptic interaction. The APSIL library (Huang, Qu, & Kaufman, 1998) is an extension of GHOST. The Stony Brook group has developed successful demonstrations of volume rendering with haptic interaction from Computer Tomography data of a lobster, a human brain, and a human head, simulating stiffness, friction, and texture solely from the volume voxel density. The development of the new interface may facilitate working directly with the volumetric representations of the objects obtained through view synthesis methods.

The surface texture of an object can be displacement mapped with thousands of tiny polygons (Srinivasan & Basdogan, 1997), although the computational demand is such that

force discontinuities can occur. More commonly, a "texture field" can be constructed from 2D image data. For example, as described above, Ikei, Wakamatsu, and Fukuda (1997) created textures from images converted to grayscale, then enhanced them to heighten brightness and contrast, such that the level and distribution of intensity corresponds to variations in the height of texture protrusions and retractions.

Surface texture may also be rendered haptically through techniques like force perturbation, where the direction and magnitude of the force vector is altered using the local gradient of the texture field to simulate effects such as coarseness (Srinivasan & Basdogan, 1997). Synthetic textures, such as wood, sandpaper, cobblestone, rubber, and plastic, may also be created using mathematical functions for the height field (Anderson, 1996; Basdogan, Ho, & Srinivasan, 1997). The ENCHANTER environment (Jansson, Faenger, Konig, & Billberger, 1998) has a texture mapper which can render sinusoidal, triangular, and rectangular textures, as well as textures provided by other programs, for any haptic object provided by the GHOST SDK.

In many applications of haptics, it is desirable to be able to explore and manipulate deformable objects as well as rigid-body objects like vases and teapots. One area that IMSC researchers are beginning to explore is the development of reliable vision-based control systems for robotic applications such as the acquisition of images for 3D modeling. Two topics that have been identified as crucial for the development of such systems for robotic applications (e.g., 3D and 4D modeling for haptics) are the development of self-calibrating control algorithms (Hager, Chang, & Morse, 1995) and the use of single-camera image acquisition systems in feedback control. One can use images of an object taken from multiple viewpoints to construct a 3D model of the object to be used for haptics. To automate the procedure of collecting the multiple views, one needs to have a camera mounted on a computer-controlled robot arm. This is particularly important for constructing 4D models of objects whose shape is evolving (e.g., a work of art as it is being produced). From a controls perspective the research problem is to build algorithms to position the camera. The desired position can be specified directly in terms of its Cartesian coordinates or indirectly in terms of desired locations of parts of the object in the image. The latter falls in the area of vision-based control and is much more interesting, because the use of vision in the feedback loop allows for great accuracy with not very precise, therefore relatively inexpensive, robotic manipulators.

Latency

The realism of haptic rendering can be adversely affected by slow update rates, as can occur in the case of the extreme computation time required by real-time rendering of deformable objects, or the delays induced by network congestion and bandwidth limitations in distributed applications.

Floyd (1999) deals with the issue of computational latency and haptic fidelity in bit-mapped virtual environments. In traditional systems with some latency there is a lack of fidelity if, say, the user penetrates a virtual object and the lag is such that there is no immediate feedback of force to indicate that a collision has occurred and that penetration is not pos-

sible. Floyd proposes that the server inform the haptic client when the user has penetrated a surface in the environment, and where that contact occurred. The client uses this information to offset the coordinate system the user is operating in so that instead of having significantly penetrated the surface, the user is just within it, computes an appropriate force response, and caches the constraint implicit in the existence of that surface so that forces to impede further progress in that direction are computed on the client alone.

Mark and his colleagues (Mark, Randolph, Finch, van Verth, & Taylor, 1996) have proposed a number of solutions to recurring problems in haptics, such as improving the update rate for forces communicated back to the user. They propose the use of intermediate representation of force through a "plane and probe" method: A local planar approximation to the user's hand location is computed when the probe or haptic tool penetrates the plane, and the force is updated at approximately 1 kHz by the force server, while the application recomputes the position of the plane and updates it at approximately 20 kHz. Balaniuk (1999) has proposed a buffer model to transmit information to the PHANToM at the necessary rate. The buffer can also be used to implement a proxy-based calculation of the haptic forces.

Networked virtual reality (VR) applications may require that force and positional data be transmitted over a communication link between computers where significant and unpredictable delays are the norm, resulting in instability in the haptic system. The potential for significant harm to the user exists in such circumstances due to the forces that the haptic devices can generate. Buttolo, Oboe, Hannaford, and McNeely (1996) note that the addition of force feedback to multiuser environments demands low latency and high collision detection sampling rates. Local area networks (LANs), because of their low communication delay, may be conducive to applications in which users can touch each other, but for wide area networks, or any environment where the demands above cannot be met, Buttolo et al. propose a "one-user-at-a-time" architecture. While some latency can be tolerated in "static" applications with a single user and no effect of the user's action on the 3D object, in collaborative environments where users make modifications to the environment it is important to make sure that any alterations from individual clients are coordinated through the server. In effect the server can queue the users so that only one can modify the object at a time and can lock the object until the new information is uploaded to the server and incorporated into the "official" version of the virtual environment. Then and only then can the next user make a modification. Delay can be tolerated under these conditions because the haptic rendering is done on a local copy of the virtual environment at each user's station.

Hespanha, McLaughlin, and Sukhatme (Chapter 8, this volume) note that latency is a critical factor that governs whether two users can truly share a common haptic experience. They propose an algorithm where the nature of the interaction between two hosts is decided dynamically based on the measured network latency between them. Users on hosts that are near each other (low communication latency) are dynamically added to fast local groups. If the communication latency is high, users are allowed a slower form of interaction where they can touch and feel objects but cannot exert forces on them. Users within a fast local group experience true haptic collaboration since the system is able to resolve the interaction forces between them quickly enough to meet stability criteria.

Fukuda and Matsumoto (Chapter 7, this volume) have also addressed the issue of the impact of network delay on collaborative haptic environments. They conducted a study of a multiuser environment with force feedback. They found that the performance of the PHANToM is sensitive to network delay, and that their SCES (Sharing Contact Entity's State) solution demonstrated good performance, as compared to taking no countermeasure against delay. Other approaches for dealing with random time delays, including Transmission Line Modeling and Haptic Dead Reckoning, are considered in Wilson et al. (1999).

Contact Detection

A fundamental problem in haptics is to detect contact between the virtual objects and the haptic device (a mouse, a PHANToM, a glove, etc.). Once this contact is reliably detected, a force corresponding to the interaction physics is generated and rendered using the probe. This process usually runs in a tight servo loop within a haptic rendering system. Lin et al. (1998, 1999) have proposed an extensible framework for contact detection that deconstructs the workspace into regions and at runtime identifies the region(s) of potential contacts. The algorithm takes advantage of temporal and spatial coherence by caching the contact geometry from the immediately prior step to perform incremental computations. Mascarenhas et al. (Chapter 5, this volume) report on a recent application of this system to the visualization of polygonal and scientific datasets. The contact detection problem is well studied in computer graphics. The reader is referred to Held (1995) and to Lin and Gottschalk (1998) for a survey.

Another technique for contact detection is to generate the so-called surface contact point (SCP), which is the closest point on the surface to the actual tip of the probe. The force generation can then happen as though the probe were physically at this location rather than within the object. Existing methods in the literature generate the SCP by using the notion of a god-object (Zilles & Salisbury, 1995), which forces the SCP to lie on the surface of the virtual object. A technique which finesses contact point detection using a voxel-based approach to 6 DOF haptic rendering is described in McNeely et al. (1999). The authors use a short-range force field to repel the manipulated object in order to maintain a minimum separation distance between the (static) environment and the manipulated object. At USC's IMSC, the authors are developing algorithms for SCP generation that use information from the current contact detection cycle and *past* information from the contact history to predict the next SCP effectively. As a first step, we are experimenting with a well-known linear predictor, the Kalman Filter, by building on our prior results in applying similar techniques to the problem of robot localization (Roumeliotis, Sukhatme, & Bekey, 1999).

Force Feedback

Two requirements drive the force feedback research in haptics: high fidelity rendering and stability. It turns out that these two goals are somewhat conflicting because high fidelity

haptic rendering generally calls for high force-feedback gains that often lead to self-induced oscillations and instability.

Inspired by electrical networks, Adams and Hannaford (1999) regard the haptic interface as a two-port system terminated on one side by the human operator and on the other side by the virtual environment (cf. Figure 1-1). The energy exchange between the human operator and the haptic interface is characterized by a force F_h and velocity v_h, whereas the exchange between the interface and the simulated virtual environment is characterized by a force F_e and velocity v_e. For ideal rendering, the haptic interface should be transparent (in the sense that $F_h = F_e$ and $v_h = v_e$), but stability requirements generally force the designer of the haptic interface to introduce some haptic distortion.

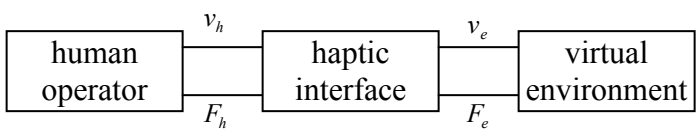

Figure 1-1: Two-port framework for haptic interfaces.

It is generally assumed that a human operator interacting with a haptic interface behaves passively (Hogan, 1989) in the sense that he or she does not introduce energy in the system. Since most mechanical virtual environments are also passive, the stability of the overall system could be guaranteed by simply designing the interface to be passive. However, as observed by Colgate, Grafing, Stanley, and Schenkel (1993), time-sampling can destroy the natural passivity of a virtual environment. In fact, these authors showed that the smaller the sampling rate, the more energy can be "generated" by a virtual wall.

Several approaches have been proposed to deal with this difficulty. Colgate and Schenkel (1997) determined conditions on the simplest virtual environment (the virtual wall) that guarantee the stability of the haptic interface for any passive human operator. These conditions reflect the fact that the amount of energy generated by a time-discretized virtual wall depends on the sampling rate. They also involve the virtual wall's stiffness and damping coefficient, posing constraints on the range of stiffness/damping parameters that can be rendered. This range is referred to by Colgate and Brown (1994) as the *z*-width of the haptic interface and is an important measure of its performance.

Adams and Hannaford (1999) followed a distinct approach by advocating the introduction of virtual coupling in the haptic interface so as to guarantee the stability of the system *for any continuous-time passive virtual environment*, even if its discrete-time version is no longer passive. The virtual coupling can be designed to provide sufficient energy dissipation to guarantee the stability of the overall system for any passive virtual environment. This approach decouples the haptic interface control problem from the design of the virtual envi-

ronment. Miller, Colgate, and Freeman (1999) extended this work to virtual environments that are not necessarily passive. The drawback of virtual coupling is that it introduces haptic distortion (because the haptic interface is no longer transparent). Hannaford, Ryu, and Kim (Chapter 3, this volume) present a new method to control instability that depends on the time domain definition of passivity. They define the "Passivity Observer," and the "Passivity Controller," and show how they can be applied to haptic interface design in place of fixed-parameter virtual couplings. This approach minimizes haptic distortion.

The work described above assumes that the human operator is passive, but poses no other constraints on her behavior. This can lead to small *z*-width, significant haptic distortion, or both. Tsai and Colgate (1995) tried to overcome this by modeling the human as a more general discrete-time linear time-invariant system. They derive conditions for stability that directly exclude the possibility of periodic oscillations for a virtual environment consisting of a virtual wall. Gillespie and Cutkosky (1996) address the same issue by modeling the human as a second order continuous-time system. They conclude that to make the approach practical, online estimation of the human mechanical model is needed, because the model's parameters change from operator to operator and, even with the same operator, from posture to posture. The use of multiple-model supervisory control (Anderson et al., 1999; Hespanha et al., 2001; Morse, 1996) to estimate online the operator's dynamics promises to bring significant advantages to the field, because it is characterized by very fast adaptation to sudden changes in the process or the control objectives. Such changes are expected in haptics due to the unpredictability of the human-in-the-loop. In fact, it is shown in Hajian and Howe (1995) that changes in the parameters of human limb dynamics become noticeable over periods of time larger than 20 ms.

Although most of the work referenced above focuses on simple prototypical virtual environments, a few researchers developed systems capable of handling very complex ones. Ruspini and Khatib (Chapter 2, this volume) are among these, having developed a general framework for the dynamic simulation and haptic exploration of complex interaction between generalized articulated virtual mechanical systems. Their simulation tool permits direct "hands-on" interaction with the virtual environment through the haptic interface.

Capture, Storage, and Retrieval of Haptic Data

One of the newest areas in haptics is the search for optimal methods for the description, storage, and retrieval of moving-sensor data of the type generated by haptic devices. With such techniques we can capture the hand or finger movement of an expert performing a skilled movement and "play it back," so that a novice can retrace the expert's path, with realistic touch sensation; further, we can calculate the correlation between the two exploratory paths as time series and determine if they are significantly different, which would indicate a need for further training. The INSITE system (Faisal, Shahabi, McLaughlin, & Betz, 1999) is capable of providing instantaneous comparison of two users with respect to duration, speed, acceleration, and thumb and finger forces. Techniques for recording and playing back raw haptic data (Shahabi, Ghoting, Kaghazian, McLaughlin, & Shanbhag, forthcoming; Shahabi, Kolahdouzan, Barish, Zimmermann, Yao, & Fu, 2001) have been developed for the

PHANToM and CyberGrasp. Captured data include movement in three dimensions, orientation, and force (contact between the probe and objects in the virtual environment). Shahabi and colleagues address haptic data at a higher level of abstraction in Chapter 14, in which they describe their efforts to understand the semantics of hand actions (see also Eisenstein, Ghandeharizadeh, Huang, Shahabi, Shanbhag, & Zimmermann, 2001).

Haptic Data Compression

Haptic data compression and evaluation of the perceptual impact of lossy compression of haptic data are further examples of uncharted waters in haptics research (see Ortega, this volume, Chapter 6). Data about the user's interaction with objects in the virtual environment must be continually refreshed if they are manipulated or deformed by user input. If data are too bulky relative to available bandwidth and computational resources, there will be improper registration between what the user sees on screen and what he "feels." Ortega's work begins by analyzing data obtained experimentally from the PHANToM and the CyberGrasp, exploring compression techniques, starting with simple approaches (similar to those used in speech coding) and continuing with methods that are more specific to the haptic data. One of two lossy methods to compress the data may be employed: One approach is to use a lower sampling rate; the other is to note small changes during movement. For example, for certain grasp motions not all of the fingers are involved. Further, during the approaching and departing phases tracker data may be more useful than the CyberGrasp data. Vector coding may prove to be more appropriate to encode the time evolution of a multifeatured set of data such as that provided by the CyberGrasp. For cases where the user employs the haptic device to manipulate a static object, compression techniques that rely on knowledge of the object may be more useful than the coding of an arbitrary trajectory in three-dimensional space.

Haptic Collaboration

The many potential applications in industry, the military, and entertainment for force feedback in multiuser environments, where two or more users orient to and manipulate the same objects, have led to work such as that of Buttolo and his colleagues (Buttolo, Oboe, & Hannaford, 1997; Buttolo, Hewitt, Oboe, & Hannaford, 1997; Buttolo, Oboe, Hannaford, & McNally, 1996), who as noted above remind us that adding haptics to multiuser environments creates additional demand for frequent position sampling for collision detection and fast update.

It is also reasonable to assume that in multiuser environments, there may be a heterogenous assortment of haptic devices with which users interact with the system. One of our primary concerns thus would be to ensure proper registration of the disparate devices with the 3D environment and with each other. Of potential use in this regard is work by Iwata, Yano, and Hashimoto (1997) on LHX (Library for Haptics), which is modular software that can support a variety of different haptic displays. LHX allows a variety of mechanical configurations, supports easy construction of haptic user interfaces, allows networked applica-

tions in virtual spaces, and includes a visual display interface. The chapter by Hespanha, McLaughlin, and Sukhatme (Chapter 8, this volume) proposes an architecture for distributed haptic collaboration with heterogeneous devices.

There have only been a few studies of cooperation/collaboration between users of haptic devices. In a study by Basdogan, Ho and their colleagues (Basdogan, Ho, Slater, & Srinavasan, 1998; Ho, Basdogan, Slater, Durlach, & Srinivasan, 1998), partners at remote locations were assigned three cooperative tasks requiring joint manipulation of 3D virtual objects, such as moving a ring back and forth along a wire while minimizing contact with the wire. Experiments were conducted with visual feedback only, and with both visual and haptic feedback. Both performance and feelings of togetherness were enhanced in the dual modality condition. Performance was best when visual feedback alone was followed by the addition of haptic feedback rather than vice versa. Durlach and Slater (n.d.) note that factors that contribute to a sense of copresence include being able to observe the effect on the environment of actions by one's interlocutors, and being able to work collaboratively with copresent others to alter the environment. Point of view (egocentric vs. exocentric) with respect to avatars may also influence the sense of copresence. Touching, even virtual touching, is believed to contribute to the sense of copresence because of its associations with closeness and intimacy.

HUMAN FACTORS

Human Haptics

The behavior of the human haptic system has been the subject of far more systematic study than has machine haptics. There are several haptically important dimensions of object recognition, including texture, hardness, shape, and thermal conductivity (Klatzky, Lederman, & Reed, 1987). Most researchers report that subjects are able to discriminate textures and to a lesser extent shapes using the haptic sense only. For example, Ballesteros, Manga, and Reales (1997) reported a moderate level of accuracy for single-finger haptic detection of raised-line shapes, with asymmetric shapes being more readily discriminated. Hatwell (1995) found that recall of texture information coded haptically was successful when memorization was intentional, but not when it was incidental, indicating that haptic information processing may be effortful for subjects.

Available evidence indicates that haptic information processing in adults involves construal of a stimulus object, such as a texture sample, as coordinates on a set of *underlying perceptual dimensions*, like “hard-soft” or “rough-smooth.” Developmental studies by Berger and Hatwell (1993, 1995) have shown that in discriminating texture samples varying with respect to the density and hardness dimensions, older subjects were less likely than younger ones to make global assessments of the stimuli and more likely to invoke the separate dimensions as judgment criteria. Hughes and Jansson (1994) note that texture gradients,

like textures, can be multidimensional and suggest candidate dimensions such as variations in the size, height, and shape of elements. Hollins, Faldowski, Rao, and Young (1993) passed samples of 17 textures over the fingertips of subjects whose view of the samples was restricted. The subjects sorted the texture samples into categories based on similarity, and then rated the samples against a series of scales measuring well-established perceptual dimensions such as roughness and hardness, and several other less-well studied potential dimensions such as "slippery-sticky." Co-occurrence data from the sorting task were converted to dissimilarities and submitted to a multidimensional scaling analysis. The researchers reported that there were two clear, orthogonal perceptual dimensions, "rough-smooth" and "soft-hard," underlying the classification of samples and speculated about a possible third dimension, "springiness."

Hughes and Jansson (1994) lament the inadequacy of embossed maps and other devices intended to communicate information through the sense of touch, a puzzling state of affairs insomuch as perception by active touch (purposeful motion of the skin surface relative to the surface of some distal object) appears to be comparatively accurate, and even more accurate than vision in apprehending certain properties such as smoothness (Hughes & Jansson, p. 302). The authors note in their critical review of the literature on active-passive equivalence that active and passive touch (as when a texture is presented to the surface of the fingers, see Hollins et al., 1993) have repeatedly been demonstrated by Lederman and her colleagues (Lederman, 1985; Lederman, Thorne, & Jones, 1986; Loomis & Lederman, 1986) to be functionally equivalent, in that touch modality does not seem to account for a significant proportion of the variation in judgments of such basic dimensions as roughness, even though the two types of touch may lead to different sorts of attributions (respectively, about the texture object and about the cutaneous sensing surface) and motor information should clearly be useful in assessing the size and distribution of surface protrusions and retractions. Active and passive touch are more likely to be equivalent in certain types of perceptual tasks; active touch should be less relevant to judgments of "hardness" than it is to assessments of "springiness." Such findings should be of interest to those working with machine haptics, as most of the application development in this field involves using the displays under conditions of active rather than passive touch.

Some researchers have reported that shape and texture recognition improve with the addition of vision, although there is not uniform agreement as to the extent of the similarity between haptic and visual information processing. Balakrishnan, Klatzky, and Loomis (1989), although reporting that length-distortion effects (attributing greater distances between two points as a path between them becomes more winding) were less pronounced under visual path tracing than had been found in previous experiments using haptic exploration, nonetheless concluded that the encoding processes are similar in the two domains. Klatzky, Lederman, and Reed (1987), however, concluded after a series of experiments that the encoding pathways are fundamentally different in the haptic and visual systems, such that the visual system is more oriented to the discrimination of shape and the haptic system to substance. Heller's work (1982) suggests that the addition of visual information about "where the hand is" (as opposed to what the surface texture looks like) is the critical contributory factor in any improved performance arising from bimodal information acquisition.

Work reported by Lederman, Thorne, and Jones (1986) indicates that the dominance of one system over the other in texture discrimination tasks is a function of the dimension of judgment being employed. In making judgments of *density*, the visual system tends to dominate, while the haptic system is most salient when subjects are asked to discriminate textures on the basis of *roughness*.

Lederman, Klatzky, Hamilton, and Ramsay (1999) studied the psychophysical effects of haptic exploration speed and mode of touch on the perceived roughness of metal objects when subjects used a rigid probe, not unlike the PHANToM stylus (see also Klatzky and Lederman, Chapter 10, this volume). In earlier work, Klatzky and Lederman found that subjects wielding rigid stick-like probes were less effective at discriminating surface textures than with the bare finger. In a finding that points to the importance of tactile arrays to haptic perception, the authors noted that when a subject is actively exploring an object with the bare finger, speed appears to have very little impact on roughness judgments, because subjects may have used kinesthetic feedback about their hand movements; however, when a rigid probe is used, people should become more reliant on vibrotactile feedback, since the degree of displacement of fingertip skin no longer is commensurate with the geometry of the surface texture.

Machine Haptics

Psychophysical studies of machine haptics are now beginning to accumulate. Experiments performed by von der Heyde and Hager-Ross (1998) have produced classic perceptual errors in the haptic domain: For instance, subjects who haptically sorted cylinders by weight made systematic errors consistent with the classical size-weight illusion. Experiments by Jansson, Faenger, Konig, and Billberger (1998) on shape sensing with blindfolded sighted observers were described above. Ernst and Banks (2001) reported that although vision usually "captures" haptics, in certain circumstances information communicated haptically (via two PHANToMs) assumes greater importance. They found that when noise is added to visual data, the haptic sense is invoked to a greater degree. Ernst and Banks concluded that the extent of capture by a particular sense modality is a function of the statistical reliability of the corresponding sensory input.

Kirkpatrick and Douglas (1999) argue that if the haptic interface does not support certain exploratory procedures, such as enclosing an object in the case of the single-point PHANToM tip, then the quick grasping of shape that enclosure provides will have to be done by techniques that the interface does support, such as tracing the contour of the virtual object. Obviously, this is slower than enclosing. The extent to which the haptic interface supports or fails to support exploratory processes contributes to its usability. Kirkpatrick and Douglas evaluated the PHANToM interface's support for the task of shape determining, comparing and contrasting its usability in three modes: vision only; haptics only; and haptics and vision combined, in a non-stereoscopic display. When broad exploration is required for quick object recognition, haptics alone is not likely to be very useful when the user is limited to a single finger whose explorations must be recalled and integrated to form an overall impression of shape. Vision alone may fail to provide adequate depth cues (e.g., the curved

shape of a teapot). Kirkpatrick and Douglas assert that the effect of haptics and vision is not additive and that the combination of them would provide a result exceeding what an additive model might predict.

Kirkpatrick and Douglas (1999) also report that among the factors that influence the speed of haptic recognition of objects are the number of different object attributes that can be perceived simultaneously and the number of fingers that are employed. This work suggests that object exploration with devices like the PHANToM, which offer kinesthetic but not cutaneous feedback, will yield suboptimal results with respect both to exploration speed and accuracy when compared to the bare hand. It further suggests that speed and accuracy may improve with additional finger receptors.

With the advent of handheld devices and the possibility of the incorporation of haptics into such devices, it is becoming increasingly important to determine just how small a haptic effect can be perceived. Dosher, Lee, and Hannaford (Chapter 12, this volume) report that users can detect haptic effects whose maximum force is about half the measured Coulomb friction level of the device and about one-third the measured static friction level. They note that their results can be expected to vary by device and that it remains to be seen whether or not a measurable effect is necessarily one that can help users accomplish their tasks.

Srinivasan and Basdogan (1997) note the importance of other modalities in haptic perception (e.g., sounds of collision with objects, etc.). They report that with respect to object deformation, visual sensing dominates over proprioception and leads to severe misjudgments of object stiffness if the graphic display is intentionally skewed (Srinavasan, Beauregard, & Brock, 1996). Sound appears to be a less important perceptual mediator than vision. In an unpublished study by Hou and Srinivasan, reported in Srinivasan and Basdogan (1997), subjects navigating through a maze were found to prefer large visual-haptic ratios and small haptic workspaces. Best results were achieved in the dual-modality condition, followed by haptic only and then vision only. It is apparent that the relative contribution of visual and haptic perception will vary as a function of task, but it is also apparent, as Srinivasan and Basdogan conclude, that the inadequacies of force-feedback display (e.g., limitations of stiffness) can be overcome with appropriate use of other modalities. In Chapter 11 Jeong and Jacobson consider the question of how effective haptic and auditory displays are when combined, whether or not they interfere with one another, and how a user's previous experience with a modality affects the success of the integration and the efficacy of the multimodal display.

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