

Haptics

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Haptic interaction with the world is manipulation using our sense of touch. The term “haptics” arises from the Greek root *haptikos*, meaning “able to grasp or perceive.” Haptic interaction with computers implies the ability to use our natural sense of touch to feel and manipulate computed quantities. Haptic computer interaction is a relatively new field that has generated considerable interest over the past decade.

A new way to interact with computers

Initially, computers could deal only with numbers. It took many years to realize the importance of operating with text. The introduction of CRT display technologies allowed graphics to be displayed, giving us a new way to interact with computers. As processing power increased over time, three-dimensional (3D) graphics became more common, and we may now peer into synthetic worlds that seem solid and almost real. Likewise, until recently, the notion of carrying on a “conversation” with our computer was far-fetched. Now, speech technology has progressed to the point that many interesting applications are being considered. Just over the horizon, computer vision is destined to play a role in face and gesture recognition. It seems clear that as the art of computing progresses, even more of the human sensory palette will become engaged.

It is likely that the sense of touch (haptics) will be the next sense to play an important role in this evolution. We use touch pervasively in our everyday lives, and are accustomed to easy manipulation of objects in three dimensions. Even our conversation is peppered with references to touching. Blake Hannaford at the University of Washington has compiled a list of verbal haptic analogies: we frequently make the analogy to haptics when we speak of our relationship to ideas, people, and information. We often use phrases like “get a feel,” “poke [into/around],” “put one's finger [on the problem],” when referring to *exploration*. We use phrases like “[to stay/keep] in touch,” “tangible [concepts],” “[a] touchy [subject],” “hands-on learning” (often used literally), and “at my fingertips” when referring to *contact*. And phrases like “pressing issues,” “pushy [behavior],” “hard hitting [presentation],” “get/lose a grasp [of the situation],” and so forth are used when referring to *impact* or *manipulation*. In fact, it is quite surprising, given our natural propensity to touch and manipulate things, that haptic computer interfaces are not common.

We principally use our hands to explore and interact with our surroundings. The hand is unique in this respect because it is both an input device and an output device: sensing and actuation are integrated within the same active living mechanism. An important question is how best to transmit haptic information between a running computer program and a user's hand. Providing position *input* to the computer from the hand is easy, providing force/torque *output* from the computer to the hand has proven to be difficult. We don't understand how to invent very good haptic devices which will link our hands in some way with a running computer program---and for that matter, we don't understand very well how best to write programs that can derive and serve up haptic information for our consumption.

Our tactile and kinesthetic senses

How does the skin detect pressure, friction, and vibration? We know the hand is a complicated system that includes articulated structure, nerves, muscles (output), and senses (input). But the hand's sensory capabilities are, at best, imperfectly understood. Because of this, fully informed design methods for haptic interfaces do not yet exist.

The sensory suite forms part of the somatosensory system which has modalities of *discriminative touch* (including touch, pressure, vibration), *proprioception* (including joint angle, muscle length and length rate of change, and

tendon tension), and *pain/temperature* (including itch and tickle). Chiefly the first two modalities are important for haptic perception.

The discriminative touch modality relies on four different kinds of receptors in the glabrous (hairless) skin of the hand. They are Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini endings. Both the Meissner's and Pacinian corpuscles are considered to be rapidly adapting (RA), responding mostly to changing stimuli, whereas the Merkel's disks and Ruffini endings are considered to be slowly adapting (SA) and continue to fire in the presence of constant stimuli. Whereas the anatomical characteristics of these receptors are known, their precise role in psychophysical perception is less well understood. The Pacinian corpuscles respond to high frequency vibrations such as those encountered when running one's finger over a textured surface. The Meissner's corpuscles are sensitive to sharp edges, the Ruffini corpuscles to skin stretch, and the Merkel's disks to edges and pressure.

The proprioception modality (kinesthesia) is also of major importance, although its receptors are less well understood compared to those of discriminatory touch. The joint angle receptors incorporate Ruffini endings and Pacinian corpuscles located at the joints, which respond to pressure applied to the receptor. Interestingly, subjects can resolve distances between thumb and forefingers corresponding to about 2.5 degrees. Muscle spindles, located between and among muscle fibers, report muscle length and rate of change of length. Being modified forms of skeletal muscle fibers, they can not only send information to the brain, but can also receive commands causing the spindle to contract, resetting its threshold setting. Golgi tendon organs, which respond to tension force within the tendons, seem to play a role in muscle control. In a haptic interface, both the proprioception and discriminative touch modalities play important roles in perception. Given these considerations, we must ask what to put (in, around, in contact with, etc.) the hand in order for a running computer program to impart a realistic sensation of touch to a user. There are many possible approaches to answering this question.

Haptic interface devices

Haptic interaction between a person and a computer requires a special device that can convert motion of the person to meaningful quantities that can be input to the computer, and at the same time, convert computed quantities to physical forces and torques that can be felt by the person. Many different kinds of devices have been invented that enable haptic interaction with the whole hand, or arm, or even the whole body. We consider here only the type of device that can be engaged by the hand. Haptic devices can have several *degrees of freedom* (DOF). For example, an ordinary mouse device has two DOFs; that is, it can be moved left/right, and also moved forward/backward, yielding two independent position measurements for input to the computer. Similarly, the familiar joystick gaming device can be tilted left/right or forward/backward, yielding two independent angles. Neither the mouse nor the joystick are haptic devices, since they provide only input to the computer. Adding motors or other actuators to these devices would permit haptic interaction, since they could then serve not only as input devices, but also as output devices.

Haptic devices with 3 DOFs allow translation in 3D, and those with 6 DOFs allow both translation and rotation in 3D. Haptic devices usually employ either serial or parallel linkages whose joint positions are measured with encoders and whose joint torques are affected by motors. One may recognize that the preceding description also applies to robot arms; in fact, many early haptic interface devices were based on robot arms. In the case of a robot arm, the computer commands the arm's joint motors to move the arm tip to a particular position and orientation in space. As a haptic device, the user holds the arm tip, moving it to a particular position/orientation as the computer monitors the joint angles. When the computed position of the tip reaches a place where motion is no longer wanted (according to the virtual environment model), the motors are turned on to provide stiff resistance to further motion. For this scheme to work, the arm must be *back-drivable*, or else the user's hand force and torque must be measured at the tip and used to control motion.

Critical considerations for haptic interface devices include degrees of freedom, *bandwidth*, *resolution*, and *stiffness range*. First of all, haptic interaction with a realistic 3D virtual environment has proven difficult with devices having fewer than 6 DOFs, but providing six-DOF capability often implies high mechanical complexity and cost. Second, the response of the device should be as "lively" as possible; otherwise interaction with the virtual environment will feel sluggish. The hand is capable of feeling frequencies of several hundred Hz, but achieving the highest possible bandwidth in an electromechanical device is challenging. Third, for the hand to feel small nuances of the virtual

environment (*e.g.*, fine texture or stick-slip friction) the device must be able to resolve extremely small changes in position and force. Finally, when the user moves through free space, nothing should be felt; when a hard virtual surface is contacted, it should feel perfectly rigid. In practical systems, neither of these objectives is achieved, however the range of possible stiffness felt by the hand should be maximized. Haptic devices primarily engage the proprioceptive senses in the hand and arm, but also involve the discriminative touch sensors, chiefly through high-frequency effects. Collectively, bandwidth, resolution, and impedance range determine the *fidelity* of the haptic device. The ideal haptic interface device has yet to be invented. One popular commercial device is a small cable-driven highly back-drivable 3-DOF arm with three encoders and three motors. A new approach uses magnetic levitation to provide 6-DOF interactions over limited ranges of motion with a single moving part.

Haptic rendering

To be able to “feel” computed quantities, there must be algorithms and computer programs capable of deriving correct force and torque values for a given situation to be output to a haptic interface device. The term *haptic rendering* is used to describe these operations, in analogy with the familiar rendering of graphics on a computer display. Normally, haptic rendering is accompanied by simultaneous graphical rendering in what is more properly referred to as a visual/haptic interface. Unlike graphical rendering which can satisfy the eye at update rates of 30 frames per second or even less, haptic rendering must be done at rates approaching a kilohertz to feel right to the hand.

In many cases, one may desire to interact haptically with three-dimensional objects modeled in the computer. For example, suppose we have modeled a cube and a cone by using mathematical formulas that define their surfaces, and we wish to be able to touch these virtual objects with a point-like probe. The haptic system establishes a one-to-one correspondence between the (virtual) probe point and the position of the haptic device handle or *manipulandum*. This is very much like the relationship between a computer mouse on the desktop and the cursor on the computer display screen. As the user moves the probe point about in three dimensions by moving the manipulandum, the computer checks whether the point is outside an object in free space or inside an object, an operation termed *collision detection*. This test must be done very rapidly, perhaps a thousand times a second. As long as the probe point is in free space, the device motors are turned off and are able to turn freely. As soon as the point is determined to be inside the virtual cube or cone, the motors are turned on providing torques to the device joints, which generate a stopping force on the manipulandum. If the user attempts to push the point farther into the virtual object, the motor currents are increased further to resist the motion. The user thus experiences a sensation of contacting the surface of a real object. With a 3-DOF haptic device, the user may freely slide the point along the surface of the cone or surfaces of the cube, feeling their shapes.

With a 6-DOF haptic device, it is possible to interact with a 3D *virtual tool* instead of just a point. The haptic system associates the position and orientation of the virtual tool with the position and orientation of the manipulandum. In our example, if the user contacts the virtual cube or cone with, say, a cube-shaped virtual tool, he or she will feel torques as well as forces, as a surface of the virtual tool rotates into contact with a surface of the cube or cone. Collision detection for a virtual tool is much more complicated than that for a point.

For either a point or virtual tool, once the virtual object surface is contacted, realistic contact forces and torques must be derived. Researchers have developed a number of different algorithms for this. For example, if the surfaces are supposed to feel rigid, a very stiff spring is modeled. If the object is deformable, its surface is modeled as a network of springs that can deform much like a mattress deforms. Surfaces of virtual objects need not be smooth. Various texture and friction rendering algorithms have been developed. In all these methods, there is a tradeoff between rendering accuracy and rendering time that is severely taxing on computer resources. There are also issues of control stability. When we interact haptically with real objects, energy is almost always dissipated, but if the interaction between a haptic device and a virtual environment is not correctly modeled, energy can be generated leading to vibration and sudden loss of control. Finding the best haptic rendering algorithms for a given situation continues to be an active area of research.

Psychophysics of haptic interaction

One may characterize the operation of a haptic interface in terms of its engineering parameters, but in the end its perception by the user is what really matters. Physiologists and psychologists have studied the human sense of touch over many decades. *Psychophysics* is the scientific study of the relationship between stimuli (specified in physical terms) and the sensations and perceptions evoked by these stimuli.

Researchers have striven to characterize and distinguish psychophysical responses from the discriminative touch sensors by performing experiments. For example, Klatzky and Lederman conducted an extensive psychophysical analysis of haptic performance under conditions where the fingertip is covered by a rigid sheath, held in place by a thin rubber glove. This eliminates the spatial pressure gradient normally provided by the mechanoreceptors (particularly the SA receptors such as the Merkel's disks) and provides only a uniform net force (with, possibly, a gradient at the edges of the sheath that is unrelated to the felt surface), simulating conditions encountered when using a haptic device.

Knowledge about the discriminatory touch modality can inform haptic interface design. It would seem that haptic sensation of subtle effects relating to texture and friction, that tend to be high-frequency phenomenon communicated mostly through the user's skin, is of major importance. It is precisely these high-frequency effects that permit a person to rapidly assess conditions in the real world. For example, when a machinist removes a part from a lathe, the first instinct is to feel the quality of the part's finish; only later is it visually inspected and measured.

Recently, psychologists have begun performing experiments to evaluate the efficacy of haptic interaction systems, *i.e.*, experiments where subjects perform tasks using only vision, or only haptics, or a combination of vision and haptics, with task performance objectively measured. For example, subjects may be asked to fit a virtual peg into a close-fitting virtual hole, with position/orientation and forces/torques on the virtual peg or virtual hole measured in real time as the task progresses. In control experiments, subjects are asked to fit a corresponding real peg into a real hole while making the same measurements. By contriving to have the experimental setup for the virtual and real cases to be nearly identical, it is possible to assess the degree of *haptic transparency* afforded by the haptic computer interaction system. It is generally found that task performance is enhanced when haptic feedback is included, but subjects experience more difficulty dealing with virtual environments than they do with real environments. Results point to the need to improve both haptic devices and haptic rendering algorithms.

How haptic computer interaction can be used

Many people think that haptic computer interaction will have widespread utility in many fields of activity. A number of application areas are under exploration, but none have as yet entered the mainstream. One such field is Computer Augmented Design (CAD) where countless products are developed for our daily use. With a visual/haptic interface, the designer of an engine can pick up and place parts into a complicated assembly while feeling the fit and friction characteristics. Haptics can be used for education and medical training. Students can learn physics involving mechanical or electromagnetic forces while actually feeling the forces. Virtual surgery can be performed, with the student feeling modeled viscoelastic properties of tissues. Multi-dimensional scientific data can be more easily understood through a visual/haptic interface where the user cannot only see the data, but feel it at any point. Haptic devices can be used as hand controllers for virtual vehicles. For example, in a flight simulator, aerodynamic forces and vibration can be transmitted to the user's hand to provide a more immersive experience. Many other potential applications are under consideration, including use by persons who are blind or visually impaired. Finally, haptics can be used to control remote machinery, such as a robot, with forces and torques reflected back to the operator.

There is growing research activity in haptics through the efforts of device designers, algorithm developers, and psychologists. As the field evolves, workers in these three seemingly disparate areas are beginning to work together and to share insights, generating new knowledge in this multidisciplinary endeavor. Meanwhile, many future applications of haptics are under consideration.

Further Reading

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Figure Captions

Figure 1:

Section of glabrous skin (schematic) showing discriminative touch sensors. (Adapted from , used with permission.)

Figure 2:

User manipulating a mechanical assembly using a haptic interface device from Sensable Technologies, Inc. (Photo courtesy of John Hollerbach, University of Utah.)