2

CHAPTER

Haptic Interfaces

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In general the word "haptic" refers to the sense of touch. This sense is essentially twofold, including both cutaneous touch and kinesthetic touch. Cutaneous touch refers to the sensation of surface features and tactile perception and is usually conveyed through the skin. Kinesthetic touch sensations, which arise within the muscles and tendons, allow us to interpret where our limbs are in space and in relation to ourselves. Haptic sensation combines both tactile and kinesthetic sensations.

The sense of touch is one of the most informative senses that humans possess. Mechanical interaction with a given environment is vital when a sense of presence is desired, or when a user wishes to manipulate objects within a remote or virtual environment with manual dexterity. The haptic display, or force-reflecting interface, is the robotic device that allows the user to interact with a virtual environment or teleoperated remote system. The haptic interface consists of a real-time display of a virtual or remote environment and a manipulator, which serves as the interface between the human operator and the simulation. The user moves within the virtual or remote environment by moving the robotic device. Haptic feedback, which is essentially force or touch feedback in a man–machine interface, allows computer simulations of various tasks to relay realistic, tangible sensations to a user. Haptic feedback allows objects typically simulated visually to take on actual physical properties, such as mass, hardness, and texture. It is also possible to realistically simulate gravitational fields as well as any other physical sensation that can be mathematically represented. With the incorporation of haptic feedback into virtual or remote environments, users have the ability to push, pull, feel, and manipulate objects in virtual space rather than just seeing a representation on a video screen.

The application of haptic interfaces in areas such as computer-aided design and manufacturing (CAD/CAM), design prototyping, and allowing users to manipulate virtual objects before manufacturing them enhances production evaluation. Along the same lines, the users of simulators for training in surgical procedures, control panel operations, and hostile work environments benefit from such a capability (Meech & Solomonides, 1996). Haptic interfaces can also be employed to provide force feedback during execution of remote tasks (known as teleoperation) such as telesurgery or hazardous waste removal. With such a wide range of applications, the benefits of haptic feedback are easily recognizable.

2.1 NATURE OF THE INTERFACE

This section describes the fundamental nature of haptic interfaces, introducing the basic components of a haptic display system, and describing in detail the capabilities of the human haptic sensing system.

2.1.1 Fundamentals of Haptic Interfaces

A haptic interface comprises of a robotic mechanism along with sensors to determine the human operator's motion and actuators to apply forces to the operator. A controller ensures the effective display of impedances, as governed by operator's interaction with a virtual or remote environment. Impedance should be understood to represent a dynamic (history-dependent) relationship between velocity and force. For instance, if the haptic interface is intended to represent manipulation of a point mass, it must exert on the user's hand a force proportional to acceleration; if it is to represent squeezing of a spring, it must generate a force proportional to displacement (Colgate & Brown, 1994). Finally, the haptic virtual environment is rendered so as to implement the desired representation.

Haptic Interface Hardware

Haptic interface hardware consists of the physical mechanism that is used to couple the human operator to the virtual or remote environment. This hardware may be a common computer-gaming joystick, a multiple degree-of-freedom (DOF) stylus, a wearable exoskeleton device, or an array of tactors that directly stimulate the skin surface. The basic components of the hardware system include the mechanism, which defines the motion capabilities of the human operator when interacting with the device; the sensors, which track operator motion in the virtual environment; and the actuators (motors), which display the desired forces or textures to the operator as defined by the environment model. The final selection of a particular mechanism, sensor, or actuator is typically governed by the target application. Tactile and kinesthetic interfaces provide tactile and kinesthetic feedback to the operator, respectively, and will be treated separately throughout the chapter. Applications where both tactile and kinesthetic feedback is desired can employ tactile displays mounted on a kinesthetic one.

Haptic Interface Control

Haptic devices are typically controlled in one of two manners—impedance or admittance control. Impedance control of a robot involves using motion input from the manipulator and calculating the corresponding forces specific to a given system model. For example, when simulating a virtual spring, when the user compresses a spring in the virtual environment, the interface applies forces to the user's hand that oppose hand motion and are proportional to spring displacement. Motion data are available from sensors on the robotic device and are sent to signal conditioning boards—typically within a desktop personal computer—for processing. The processing calculations involve two differentiations of the position data in order to find velocity and acceleration, or one differentiation to get acceleration if velocity signals are available directly (e.g., from a tachometer). Most simple simulated environments consist only of springs that produce a force proportional to displacement, and dampers that generate forces proportional to the velocity. Thus, if position and velocity signals can be obtained directly without any differentiation, impedance control of the robot is the desired approach.

Admittance control of a robot is the opposite operation. Forces are measured, usually with a load cell, and are then sent to the computer. Calculations are performed to find the corresponding motion of the endpoint according to the simulation's equations of motion, and position control approaches are used to move the robot accordingly. Solving for the output position involves one or two integration steps, depending on the environment model. Typically, integration is a much cleaner operation than differentiation, but problems with offsets and integrator windup are common and detract from this method of robot control. In practice, impedance-controlled interfaces are better at simulating soft, spongy environments, whereas admittance-controlled devices perform better when displaying hard surfaces.

Creating a Haptic Environment

A haptic environment is defined via a mathematical model. For the simple case of a virtual wall, the model of a spring and damper in parallel is typically used. The higher the stiffness of the spring, the stiffer the virtual wall appears to the user. Using the impedance control mode, where endpoint motion is measured and force is displayed, the position of the endpoint is tracked to determine if the user is pushing on the virtual wall. When the plane of the wall is crossed, the corresponding force that the user should feel is calculated according to the model equation, using position sensor data and velocity data to calculate the model unknowns. This virtual wall model is illustrated in Figure 2.1, and serves as the building block for many virtual environments. Haptic rendering will not be a

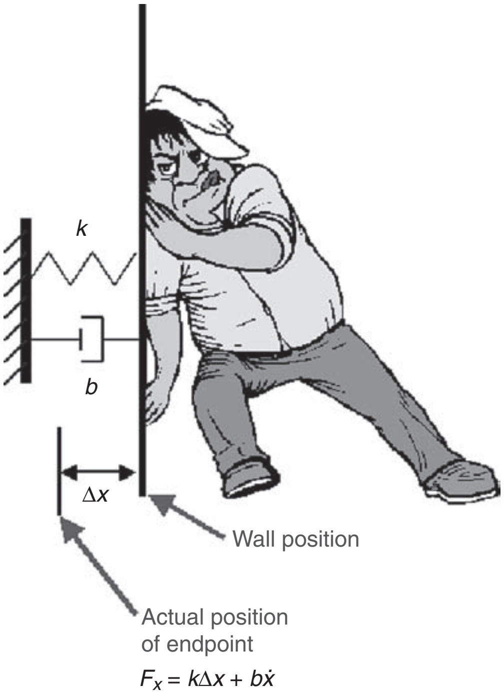

FIGURE 2.1 Graphical representation of a virtual wall model.
The virtual wall is a fundamental building block of a haptic virtual environment. It is typically implemented as a spring and damper in parallel.

focus of this chapter. However, thorough reviews and introductions to the basic concepts of haptic rendering are available, such as work by Salisbury et al. (2004).

2.1.2 Human Haptic Sensing

Touch can be defined as the sensation evoked when the skin is subjected to mechanical, thermal, chemical, or electrical stimuli (Cholewiak & Collins, 1991). Touch is unlike any other human sense in that sensory receptors related to touch are not associated to form a single organ. Haptic receptors are of three independent modalities: pressure/touch (mechanoreceptors), heat and cold (thermoreception), and pain (nociception) (Schmidt, 1977). As the mechanoreceptors are responsible for tactile sensation of pressure/touch, and are the primary targets of tactile haptic devices, this section will focus on the pressure/touch modality. Kinesthetic haptic feedback is Au1 sensed through receptors in muscles and tendons, and is discussed in Section 2.1.3.

Mechanoreception comprises four qualities: the sensations of pressure, touch, vibration and tickle. The distribution of these receptors is not uniform over the body. Hairless (glabrous) skin has five kinds of receptors: free receptors (or nerve endings), Meissner corpuscles, Merkel's disks, Pacinian corpuscles, and Ruffini corpuscles. In addition to these receptors, hairy skin has the hair-root plexus (or follicle) that detects movement on the surface of the skin. Figure 2.2 depicts the location of these receptors in the skin. Each of these mechanoreceptors respond differently to applied pressure/touch stimuli and their combined behavior determines human perception of pressure and vibrations. The study of these properties is critical to successful design of haptic interfaces for temporal as well as spatial detection and/or discrimination by the user.

Sensory adaptation is the tendency of a sensory system to adjust as a result of repeated exposure to a specific type of stimulus. Based on the rate of sensory adaptation, the receptors are classified as slow-adapting (SA) or rapid-adapting

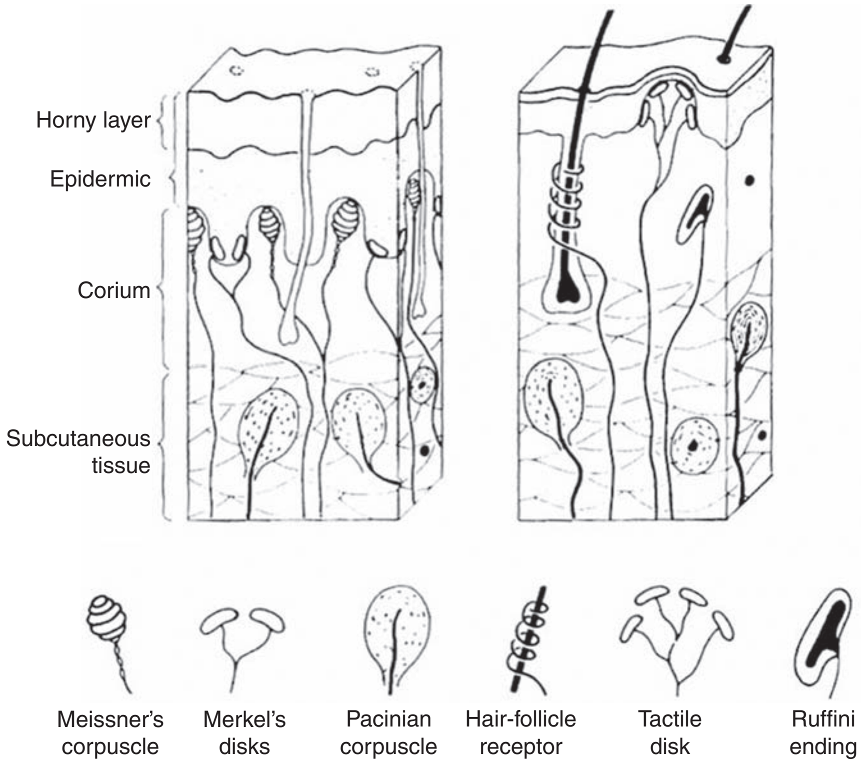

FIGURE 2.2 Structure and location of tactile receptors in the skin.
Source: From Schmidt (1977).

(RA) receptors. Merkel disks produce a long but irregular discharge rate in response to forces on the skin, whereas Ruffini corpuscles produce a regular discharge for a steady load. Meissner corpuscles discharge mostly at the onset of stimulus, and hence best respond to velocity. Finally, Pacinian corpuscles respond once for every stimulus and are good only as vibration detectors, responding best to frequencies of 200 Hz, which is their lowest stimulus amplitude threshold (Schmidt, 1977). Hence, when designing high-frequency vibrotactile feedback, for example, the behavior of Pacinian corpuscles must be considered to ensure proper detection and discrimination of the stimuli by the user, whereas at lower frequencies, the behavior of other receptors needs to be considered as well.

Mechanoreceptors can also be characterized based on their receptive field size. This is the area in which a stimulus can excite the receptor, and varies from 1 to 2 mm^2 to up to 45 mm^2 depending on the receptor and location on the body. Pacinian and Ruffini corpuscles have large field size and hence low spatial resolution. On the other hand, Merkel disks and Meissner corpuscles provide more accurate spatial localization. This is particularly important in tactile display design, as cues that cannot be discriminated by the user will fail to convey any additional information about the simulated environment.

The skin's thermoreceptors are divided into cold- and warmth-sensitive receptors. The former are located just beneath the epidermis, while the latter are located in the dermis. These receptors have a receptive field of 1 to 2 mm in diameter, and a spatial resolution that is less than that of pain receptors or mechanoreceptors. Tissue-damaging stimuli trigger nociceptors. These have a receptive field of approximately 25 mm^2.

Haptic interface designers should ensure that the force feedback is sufficient for satisfactory completion of a task while at the same time being comfortable for the user. This requires particular attention to the perceptual capabilities of the human sensorimotor loop, which are discussed in the following sections.

2.1.3 Human Haptic Perception

Human haptic perception (rather than sensing, discussed previously) is the process of acquiring, interpreting, selecting, and organizing haptic sensory information, and is comprised of tactile perception and kinesthesia (including proprioception). Kinesthesia refers to the sense of force within the muscles and tendons, and proprioception refers to the human perception of one's own body position and motion. The sense of position refers to angle of various skeletal joints, and the sensitivity or resolution of joint position determines the accuracy with which we can control our limbs. Tactile perception specifically concerns the acquisition and interpretation of sensations realized through the mechanoreceptors of the skin.

Many scientists have studied human perception thresholds in order to understand the limits of our abilities. Since human sense of touch inherently takes place through two separate pathways, namely kinesthetic and tactile information pathways, perception studies in human sense of touch can also be categorized with respect to the fundamental information contained within the stimuli. Irrespective of whether the dominant pathway is kinesthetic or tactile, existing studies have looked at discrimination or identification of surface properties (e.g., shape and surface texture) and volumetric properties (e.g., mass and sponginess) of objects.

Current studies of the just noticeable differences (JNDs) for kinesthetic and tactile senses have focused on discrimination of geometries, textures, and volumetric properties of objects held by the human, or have focused on discrimination of the subject's own limb movements; see Durlach and Mavor (1995) for a comprehensive review. The JND is the smallest difference in a specified modality of sensory input that is detectable by a human. It is also referred to as the difference limen or the differential threshold.

Early kinesthetic studies by Clark and colleagues and Jones and Hunter (Clark & Horch, 1986; Clark, 1992; Jones & Hunter, 1992) investigated human perception of limb positions and concluded that humans are capable of detecting joint rotations of a fraction of a degree performed over a second of time interval. Jones and Hunter (1992) also reported the differential threshold for limb movement as 8 percent. Further psychophysical experiments conducted by Tan and colleagues (1994) determined the JND for the finger joints as 2.5 percent, for the wrist and elbow as 2 percent, and for the shoulder as 0.8 percent.

Durlach and colleagues (1989) investigated the length resolution for rigid objects held in a pinch grasp between the thumb and the forefinger (Durlach et al., 1989). Commonly accepted perception thresholds for length resolution are given as about 1 mm for a reference length of 10 mm, increasing to 2 to 4 mm for a reference length of 80 mm. For purposes of comparison, the thickness of a penny is approximately 1.57 mm, whereas its diameter is about 19 mm.

Later experiments focusing on object size characterized the effect of varying levels of force output and virtual surface stiffness on the ability of human subjects to perform size identification and size discrimination tasks in a simulated environment (O'Malley & Goldfarb, 2002, 2004; Upperman et al., 2004; O'Malley & Upperman, 2006). In an application where haptic cues are provided for navigation, detection of the stimuli is important and not their discrimination from each other. In such a scenario, low forces and virtual surface stiffness may suffice. Note that these cues will feel soft or squishy due to low force and stiffness levels. On the other hand, tasks that require size discrimination, such as palpation in a medical trainer, require larger force and stiffness values, and consequently, a haptic interface capable of larger force output and of higher quality. Recently, McKnight and colleagues (2004) extended these psychophysical size discrimination experiments to include two- and three-fingered grasps.

The bandwidth of the kinesthetic sensing system has been estimated at 20 to 30 Hz (Brooks, 1990). In other words, the kinesthetic sensing system cannot sense movements that happen more frequently than 30 times in a second. Hence, in studies on perception of high-frequency vibrations and surface texture, the tactile pathway serves as the primary information channel, whereas the kinesthetic information is supplementary. Early tactile perception studies concluded that the spatial resolution on the finger pad is about 0.15 mm for localization of a point stimulus (Loomis, 1979), and about 1 mm for the two-point limen (Johnson & Phillips, 1981). Other parts of the body have much less spatial resolution. For example, the palm cannot discriminate between two points that are less than 11 mm apart (Shimoga, 1993).

A related measure, the successiveness limen (SL), is the time threshold for which subjects are able to detect two successive stimuli. An approximate SL value for the mechanoreceptors is 5 msec, with a required interval of 20 msec to perceive the order of the stimuli. The human threshold for the detection of vibration of a single probe is reported to be about 28 dB for the 0.4- to 3-Hz range. An increase in level of 6 dB represents a doubling of amplitude, regardless of the initial level. A change of 20 dB represents a change in amplitude by a factor of 10. This threshold is shown to decrease at the rate of −5 dB per octave in the 3- to 30-Hz range, and at the rate of −12 dB per octave in the 30- to about 250-Hz range, with an increase for higher frequencies (Rabinowitz et al., 1987; Bolanowski et al., 1988).

2.1.4 Sensory Motor Control

In addition to tactile and kinesthetic sensing, the human haptic system includes a motor subsystem. Exploratory tasks are dominated by the sensorial part of the sensory motor loop, whereas manipulation tasks are dominated by the motor part (Jandura & Srinivasan, 1994). The key aspects of the human sensorimotor control are maximum force exertion; force tracking resolution; compliance, force, and mass resolution; finger and hand mechanical impedance; and force control bandwidth.

Maximum Force Exertion

A maximum grasping force of 400 N for males and 228 N for females was measured in a study by An and coworkers (An et al., 1986). In a study on maximum force exertion by the pointer, index, and ring fingers, it was found that the maximum force exerted by the pointer and index fingers was about 50 N, whereas the ring finger exerted a maximum force of 40 N (Sutter et al., 1989). These forces were found to be constant over 0 to 80 degrees of the metacarpal (MCP) joint angle. This work was later extended to include the proximal-inter-phalangeal (PIP) joints and MCP joints, as well as the wrist, elbow, and shoulder (with arm extended to the side and in front) (Tan et al., 1994). Note that the maximum force exertion capability is dependent on the user's posture. It was found that maximum force exertion grows from the most distal joint in the palm to the most proximal one (shoulder). In addition, it was found that controllability over the maximum force decreased from the shoulder to the PIP joint. In order to ensure user safety, a haptic interface should never apply forces that the user cannot successfully counter.

Sustained Force Exertion Prolonged exertion of maximum force leads to fatigue. Fatigue is an important consideration when designing feedback for applications like data visualization where force feedback may be present for extended periods of time. Wiker and colleagues (1989) performed a study of the relationship between fatigue during grasping as a function of force magnitude, rest duration, and progression of the task. The tests showed a direct correlation between magnitude of discomfort and magnitude of pinch force. The work versus rest ratio was not found to be important for low forces but was effective in reducing fatigue for high pinch forces.

Force Tracking Resolution

Force tracking resolution represents the human ability to control contact forces in following a target force profile. Srinivasan and Chen (1993) studied fingertip force tracking in subjects using both constant and time-varying (ramp and sinusoids) forces. For some participants, a computer monitor provided a display of both the actual and target forces. Subjects also performed the tests under local cutaneous anesthesia. It was found that when no visual feedback was available, the absolute error rate increased with target magnitude. When visual feedback was present, the error rate did not depend on target magnitude.

Compliance Resolution

Compliance, or softness, resolution is critical in certain applications such as training for palpation tasks or telesurgery, since many medical procedures require accurate discrimination of tissue properties. The following discussion presents a short summary of the literature on compliance resolution both with and without the presence of additional visual or auditory clues. If a haptic interface is to be used for exploratory tasks that require discrimination among objects based on their compliance, then designers should ensure that the simulated virtual objects appear sufficiently different to the human operator.

Human perception of compliance involves both the kinesthetic and tactile channels since spatial pressure distribution within the contact region sensed through the tactile receptors plays a fundamental role in compliance perception. However, for deformable objects with rigid surfaces, the information available through the tactile sense is limited and kinesthetic information again becomes the dominant information channel. In such cases, human perceptual resolution is much lower than the cases for compliant objects with deformable surfaces (Srinivasan & LaMotte, 1995). In studies involving deformable objects with rigid surfaces, Jones and Hunter (1990, 1992) reported the differential thresholds for stiffness as 23 percent. Tan and colleagues (1992, 1993) observed that for such objects held in a pinch grasp, the JND for compliance is about 5 to 15 percent when the displacement range is fixed, and 22 percent when displacement range is randomly varied. Moreover, they reported a minimum stiffness value of 25 N/m (Newtons per meter) for an object to be perceived as rigid (Tan et al., 1994).

In further studies, Tan and coworkers (1995) investigated the effect of force work cues on stiffness perception and concluded that JND can become as high as 99 percent when these cues are eliminated. Investigating the effect of other cues on compliance perception, DiFranco and colleagues (1997) observed the importance of auditory cues associated with tapping harder surfaces and concluded that the objects are perceived to be stiffer when such auditory cues are present.

In a similar study, Srinivasan and coworkers (1996) reported dominance vision in human stiffness perception. In related studies, Durfee et al. (1997) investigated the influence of haptic and visual displays on the stiffness perception, while O'Malley and Goldfarb (2004) studied the implications of surface stiffness for size identification and perceived surface hardness in haptic interfaces. Observing the importance of the initial force rate of change in stiffness perception, Lawrence and colleagues (2000) proposed a new metric for human perception of stiffness, called rate-hardness.

Force Resolution

In related experiments, human perceptual limitations of contact force perception—when the kinesthetic sense acts as the primary information channel—have been studied. The JND for contact force is shown to be 5 to 15 percent of the reference force over a wide range of conditions (Jones. 1989; Pang et al., 1991; Tan et al., 1992). Accompanying experiments revealed a JND value of about 10 percent for manual resolution of mass (Tan et al., 1994), while a JND value of about 34 percent has been observed for manual resolution of viscosity (Jones & Hunter, 1993). Recently, Barbagli and colleagues (2006) studied the discrimination thresholds of force direction and reported values of 25.6 percent and 18.4 percent for force feedback only and visual augmented force feedback conditions, respectively. Special attention is required when designing feedback for applications like grasping and manipulation, where subtle changes in force can be important, such as in making the difference between holding and dropping an object in the virtual environment.

Mechanical Impedance

The impedance of the human operator's arm or finger plays an important role in determining how well the interface performs in replicating the desired contact force at the human-machine contact point. Hajian and Howe (1997) studied the fingertip impedance of humans toward building a finger haptic interface. Over all subjects and forces, they estimated the equivalent mass to vary from 3.5 to 8.7 g, the equivalent damping at 4.02 to 7.4 Ns/m, and stiffness at 255 to

1255 N/m. It was noted that the damping and stiffness increased linearly with force. In similar work, Speich and colleagues (2005) built and compared two- and five-DOF models of a human arm toward design of a teleoperation interface.

Sensing and Control Bandwidth

Sensing bandwidth refers to the frequency with which tactile and/or kinesthetic stimuli are sensed, and control bandwidth refers to the frequencies at which the human can respond and voluntarily initiate motion of their limbs. In humans, the input (sensory) bandwidth is much larger than the output bandwidth. As noted earlier, it is critical to ensure that the level of haptic feedback is sufficient for task completion while being comfortable for the user. In a review paper, Shimoga (1992) showed that the hands and fingers have a force exertion bandwidth of 5 to 10 Hz, compared to a kinesthetic sensing bandwidth of 20 to 30 Hz (Shimoga, 1992). Tactile sensing has a bandwidth of 0 to 400 Hz. Keeping this in mind, if we design an application that requires repetitive force exertion by the user, to guarantee user comfort the required rate should not be more than 5 to 10 times a second. Similarly, any kinesthetic feedback to the user should be limited to 20 to 30 Hz.

2.2

TECHNOLOGY OF THE INTERFACE

Haptic interfaces are a relatively new technology, with increased use for human interaction with virtual environments since the early 1990s. A primary indicator of the increased proliferation of haptic devices is the number of companies that now market devices, including Sensable Technologies, Immersion, Force Dimension, Quanser, and Novint, among others. The commercialization of haptic devices is due primarily to technological advances that have reduced the cost of necessary components in haptic systems, including materials, actuation, sensing, and computer control platforms.

Novel materials, such as carbon fiber tubing, have enabled the design and fabrication of light-weight yet stiff kinematic mechanisms that are well suited to the kinesthetic type of haptic display. Power-dense actuators, such as brushless DC motors, have allowed for increased magnitude force output from haptic devices with minimal trade-offs in terms of weight. However, it should be noted that actuation technology is still a key limitation in haptic device design, since large forces and torques obtained via direct drive actuation are often desired, while still achieving minimal inertia (mass) in the mechanism. Improved sensor technology has also enabled an increase in the availability of high-quality haptic interface hardware. The key requirement of sensors for haptic applications is high resolution, and many solutions such as optical encoders and noncontact potentiometers are providing increased resolution without compromising the back-driveability of haptic devices due to their noncontact nature.

The final set of technological advances is in the area of computational platforms. First, data acquisition systems, which enable transformation from analog and digital signals common to the sensors and actuators to the digital computation carried out by the control computer, are achieving higher and higher resolutions. Second, real-time computation platforms and increasing processor speeds are enabling haptic displays (typically rendered at a rate of 1000 Hz) to exhibit increasingly greater complexity in terms of computation and model realism. This is in turn broadens the range of applications for which haptic feedback implementation is now feasible. Finally, embedded processors and embedded computing are enabling haptic devices to be more portable.

2.3

CURRENT INTERFACE IMPLEMENTATIONS

Over the last several years, a variety of haptic interfaces have been developed for various applications. They range from simple single-DOF devices for research (Lawrence & Chapel, 1994) to complex, multi-DOF wearable devices (Frisoli et al., 2005; Kim et al., 2005; Gupta & O'Malley, 2006). DOF refers to the number of variables required to completely define the pose of a robot. A higher-DOF device has a larger workspace—the physical space within which the robot endpoint moves—as compared to a low-DOF device of similar size. Haptic devices are also used in various applications (Hayward et al., 2004). For instance, haptic interfaces have been employed for augmentation of graphical user interfaces (GUIs) (Smyth & Kirkpatrick, 2006), scientific data visualization (Brooks et al., 1990), enhancement of nanomanipulation systems (Falvo et al., 1996), visual arts (O'Modhrain, 2000), CAD/CAM (Nahvi et al., 1998, McNeely et al., 1999), education and training and particularly surgical training (Delp et al., 1997), master interfaces in teleoperation (Kim et al., 2005), rehabilitation (Bergamasco & Avizzano, 1997, Krebs et al., 1998), and the scientific study of touch (Hogan et al., 1990, Weisenberger et al., 2000).

The PHANToM desktop haptic interface (Sensable Inc.), shown in Figure 2.3, is probably the most commonly used haptic interface. It is a pen- or stylus-type haptic interface, where the operator grips the stylus at the end of the robot during haptic exploration. The PHANToM desktop device has a workspace of about 160 W × 120 H × 120 D mm. The device provides feedback to the operator in three dimensions with a maximum exertable force capability of 1.8 foot-pounds (lb_f) (7.9 N) and a continuous exertable force capability (over 24 hours) of 0.4 lb_f (1.75 N). A number of device models are available that vary in workspace and force output specifications. Several other haptic interfaces are commercially available, such as the six-DOF Delta haptic device (Force Dimension), three-DOF planar pantograph (Quanser Inc.), and the force-feedback hand controller (MPB Technologies) (Figure 2.3).

The common feature of most commercially available haptic devices is that they are point contact devices, in that the endpoint of the robot is mapped to a

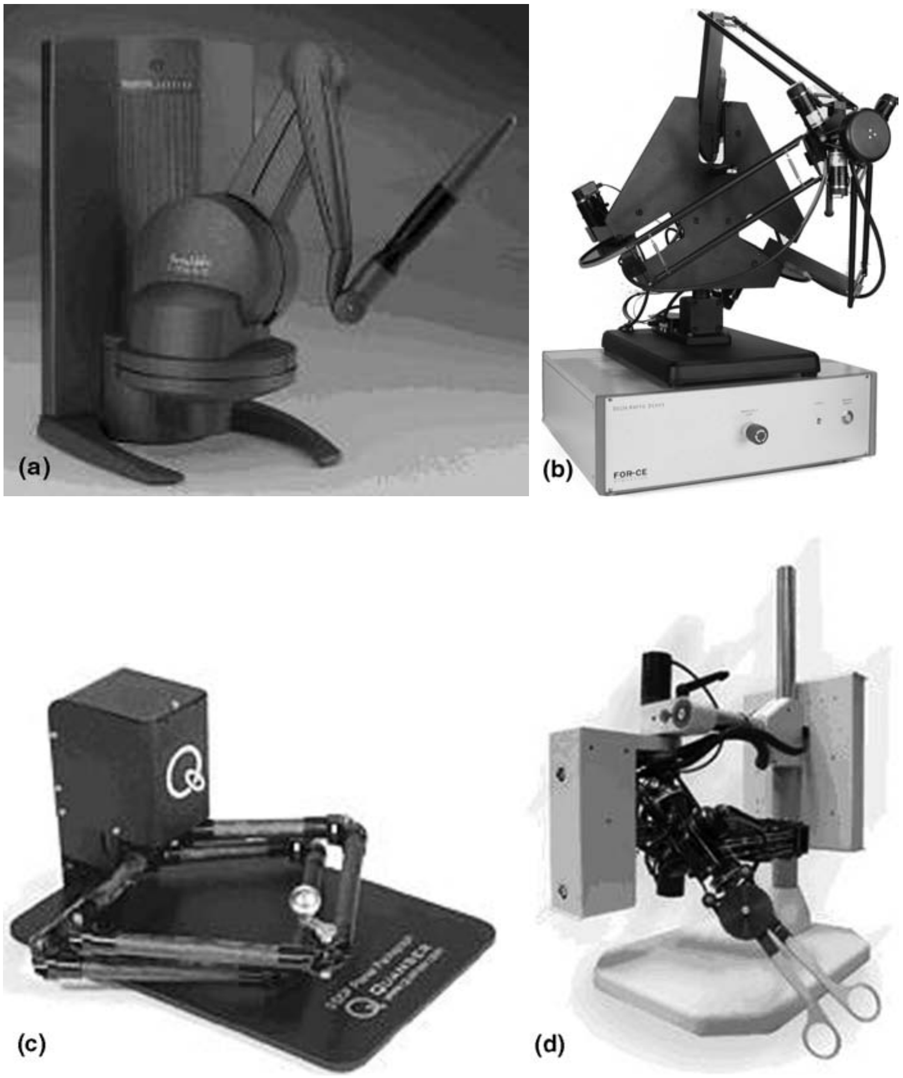

FIGURE 2.3 Selected commercially available haptic interfaces.
(a) PHANToM desktop (Sensable Inc.); (b) six-DOF Delta haptic interface (Force Dimension); (c) three-DOF planar pantograph (Quanser Inc.); and (d) force-feedback hand controller. (Courtesy of (a) SensAble Technologices, Inc.; (b) Force Dimension; (c) Quanser Inc.; (d) MPB Technologies Inc.)

position in the virtual environment and forces are applied back to the user at the same point. Thus, within the virtual environment, the user can interact with only one point. One can think of this as being similar to interacting with objects in the real world with the aid of tools like a pen, screwdriver, or scalpel. Even with this limitation, these types of devices have been employed in applications such as scientific visualization, augmentation of GUIs, CAD, and psychophysical studies. The choice of a specific device depends on the desired workspace and DOF, the type of force feedback desired, and the magnitude of forces to be displayed. For example, the PHANToM can move within the three-dimensional (3D) physical space, but can apply forces only on the user's hands. In comparison, the three-DOF pantograph is restricted to moving in a plane, but can apply a torque or wrench to the user's hand in addition to forces in the two planar directions.

In the following subsections, we take a closer look at selected current implementations of haptic interfaces. The examples presented have been chosen to demonstrate essential features, and do not necessarily represent the state of the art, but rather basic features of their respective categories. These devices demonstrate the wide range of technologies involved in haptics.

2.3.1 Nonportable Haptic Interfaces

Haptic Joysticks

Joysticks are widely used as simple input devices for computer graphics, industrial control, and entertainment. Most general-purpose joysticks have two DOF with a handle that the user can operate. The handle is supported at one end by a spherical joint and at the other by two sliding contacts (Figure 2.4). Haptic joysticks vary both in mechanical design and actuation mechanisms. Adelstein and Rosen (1992) developed a spherical configuration haptic joystick for study of hand tremors. Spherical joysticks, as the name implies, have a sphere-shaped workspace. Cartesian joysticks, on the other hand, have two or three orthogonal axes that allow the entire base of the handle to translate. An example is the three-DOF Cartesian joystick comprised of a moving platform sliding using guiding blocks and rails proposed by Ellis and colleagues (1996). The moving block supports an electric motor that actuates the third DOF (rotation about z-axis). This Cartesian joystick (Figure 2.5) has a square-shaped planar workspace, and each axis is actuated using DC motors and a cable transmission.

Other examples of haptic joysticks include a four-DOF joystick based on the Stewart platform (Millman et al., 1993) and a magnetically levitated joystick (Salcudean & Vlaar, 1994). The magnetically levitated joystick has no friction at all and is particularly suited for display of small forces and stiff contact.

These haptic joysticks are point contact devices, and each type varies according to workspace shape and size. While the spherical joystick can be used with just wrist movements, Cartesian joysticks require the user to employ other joints of

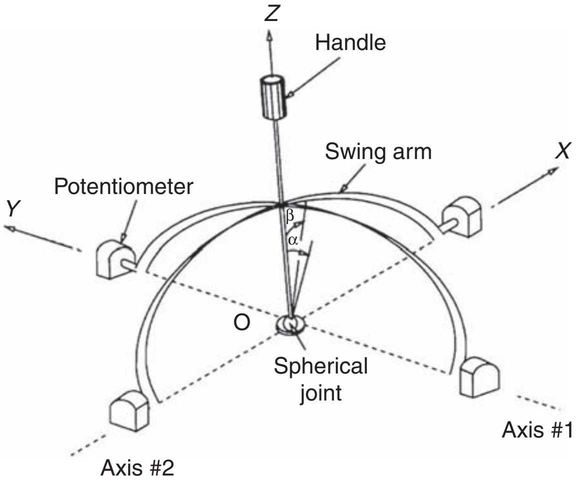

FIGURE 2.4 Two-DOF slotted swing arm joystick.
Source: From Adelstein and Rosen (1992).

the arm, like the elbow or the shoulder. Consequently, the workspace and force output of Cartesian joysticks can be greater than that of similarly sized spherical models. Note that most commercially available force-feedback joysticks, typically marketed for computer gaming applications, lack the quality necessary to achieve

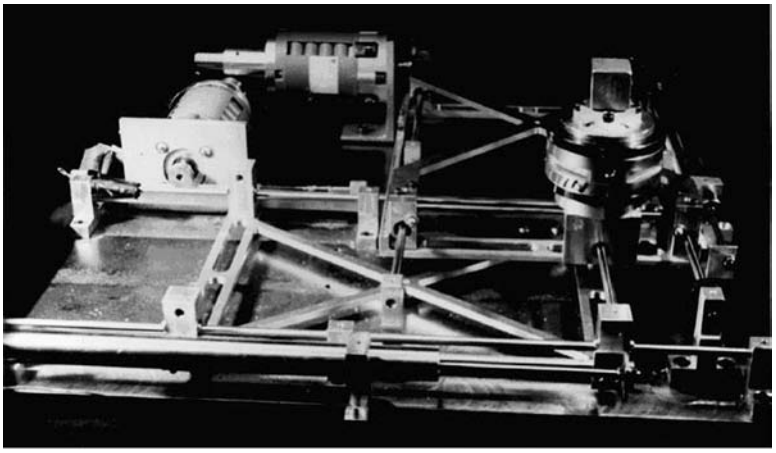

FIGURE 2.5 Three-DOF Cartesian joystick.
The joystick comprises of a central stage that moves using guiding block and rails. *Source*: From Ellis et al. (1996).

high-quality feedback for exploratory or manipulative tasks. While they may suffice to provide haptic cues that can be detected, high-quality hardware and a fast computer platform are necessary to ensure proper discrimination of cues.

Pen-Based Masters

Pen-based haptic devices allow interaction with the virtual environment through tools such as a pen (or pointer) or scalpel (in surgical simulations). These devices are compact with a workspace larger than that of spherical and magnetically levitated joysticks and have three to six DOF. The best-known example of a pen-based haptic interface is the PHANToM, mentioned earlier in this section. Originally developed by Massie and Salisbury (1994), the PHANToM is an electrically actuated serial-feedback robotic arm that ends with a finger gimbal support that can be replaced with a stylus (Figure 2.6). The gimbal orientation is passive and the serial arm applies translational forces to the operator's fingertip or hand. A six-DOF interface that can apply forces as well as torques to the operator is presented

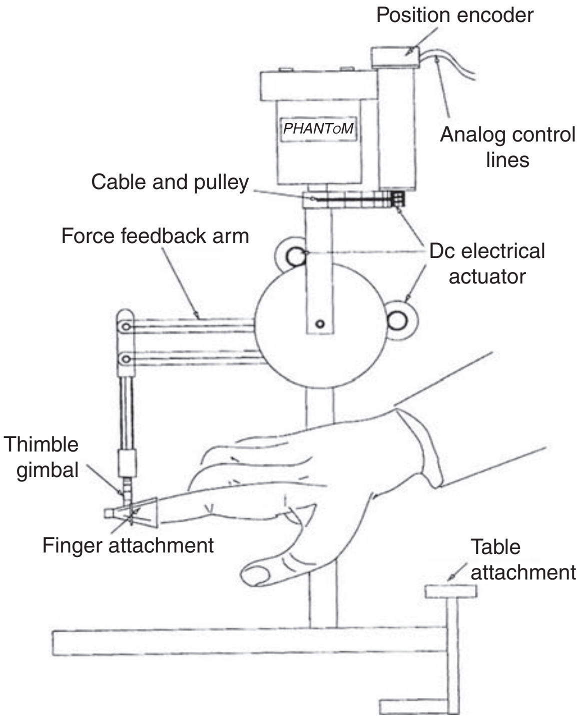

FIGURE 2.6 Schematic of PHANToM desktop haptic interface. *Source*: From Massie and Salisbury (1994).

in Iwata (1993), extending the complexity of force and torque interactions between a human operator and the remote or virtual environment.

Floor- and Ceiling-Mounted Interfaces

Generally, floor- and ceiling-mounted interfaces are larger and more complex and expensive than desktop devices. They have a large force output, and as a result, user safety becomes critical. This is especially true for exoskeletons where the operator is inside the device workspace at all times. Figure 2.7 shows one of the first generalized master arms that was developed at the National Aeronautical and Space Administration (NASA) Jet Propulsion Laboratory (JPL) (Bejczy & Salisbury, 1980). It is a six-DOF interface with a three-axis hand grip that slides and rotates about a fixed support attached to the floor. The hand grip can apply forces up to 9.8 N and torques up to 0.5 N/m. The JPL device is another example of a point contact haptic interface where the forces are applied at the user's hands. As compared to joysticks or desktop devices though, it provides a much larger work volume with greater force output capabilities, coupled with greater freedom of arm movement. These larger devices are useful for remotely manipulating large robotic manipulators like those used in space.

An example of a grounded exoskeletal haptic interface is the MAHI arm exoskeleton (Figure 2.8) built at Rice University (Gupta & O'Malley, 2006; Sledd & O'Malley, 2006). This five-DOF exoskeleton was designed primarily for rehabilitation and training in virtual environments. The device encompasses most of the human arm workspace and can independently apply forces to the elbow, forearm, or wrist joints. Note that this is no longer a point contact device, but can provide independently controlled feedback to various human joints. This feature makes it extremely suitable as a rehabilitation interface that allows the therapist to focus treatment on isolated joints.

FIGURE 2.7 Six-DOF JPL arm master.
Two hand controllers used by human operator. *Source*: From O'Malley and Ambrose (2003).

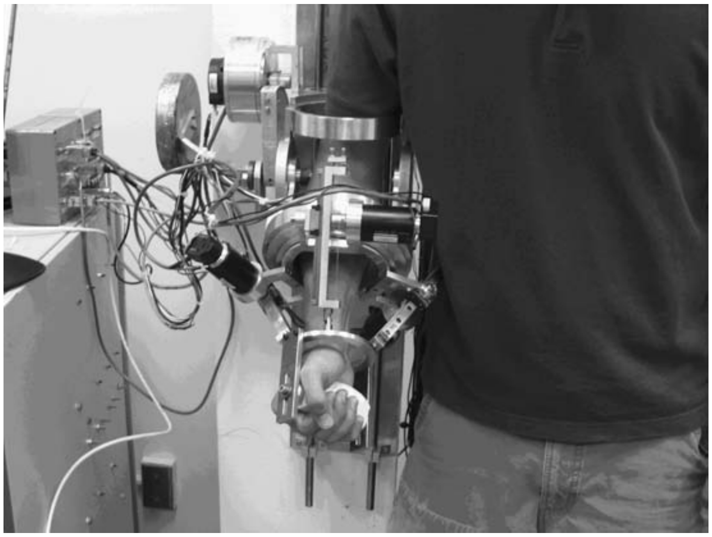

FIGURE 2.8 MAHI haptic arm exoskeleton.
The five-DOF arm exoskeleton applies forces to the operator's elbow, forearm, and wrist joints. *Source*: From Sledd and O'Malley (2006).

2.3.2 Portable Haptic Interfaces

All elements of portable haptic interfaces are worn by the user. Based on their mechanical grounding, they can be classified as arm exoskeletons or hand masters. Arm exoskeletons are typically attached to a back plate and to the forearm. Hand masters, on the other hand, are attached to user's wrist or palm. As compared to point contact devices, exoskeletal devices are capable of measuring location of various human joints and can provide feedback at multiple locations. Thus, with an exoskeleton-type interface the user is no longer restricted to interact with a single point in the workspace, but can use the whole arm as with an arm exoskeleton, or grasp and manipulate multidimensional objects using a hand master. In addition, wearable devices have a workspace that is comparable to the natural human workspace.

One of the earliest modern haptic arm exoskeletons was developed by Bergamasco and colleagues (Bergamasco et al., 1994). The five-DOF arm provides feedback to the shoulder, elbow, and forearm joints using DC motors and a complex cable transmission. The user controls the exoskeleton through a handle attached to the last rigid link. The device weighs 10 kg and can apply torque up to 20 N/m at the shoulder, 10 N/m at the elbow, and 2 N/m at the wrist joint. Recently, Bergamasco and colleagues (Frisoli et al., 2005) have developed a newer version of the device, the Light Exoskeleton (Figure 2.9), which has improved weight and torque output properties.

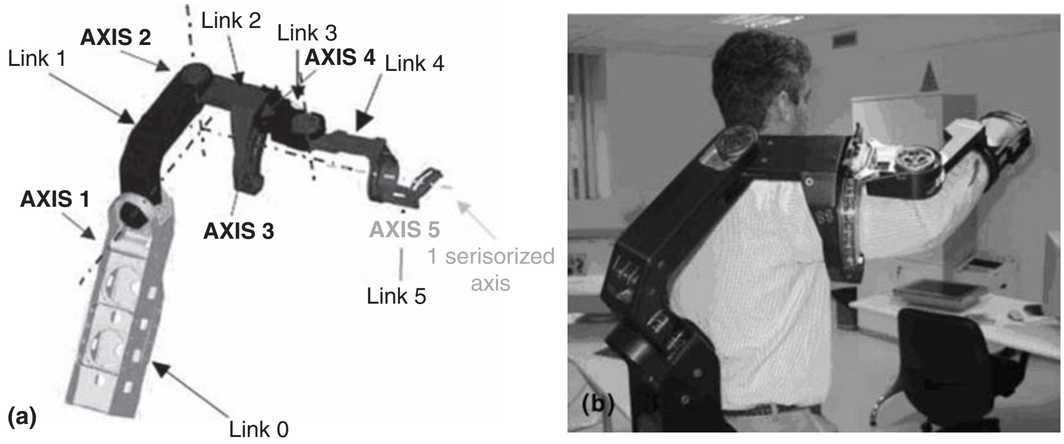

FIGURE 2.9

Light Exoskeleton (L-Exos).
(a) Kinematics. (b) Final exoskeleton. *Source*: From Frisoli et al. (2005).

An example of a portable hand master is the Rutgers Master II built at Rutgers University (Figure 2.10). The Rutgers Master II incorporates the robot's actuators into the palm of the user, thereby eliminating the need for a transmission or bulky cable routing over the backs of the fingertips. The total weight of the interface is about 100 g, and it can apply forces of up to 4 N at the fingertip. With this hand master, the positions of each of the four fingers can be separately mapped in the virtual or remote environment, and respective forces displayed back to the user. This makes it an ideal interface for tasks where grasp or manipulation of objects is desirable. Examples of such application include palpation, virtual tours of homes and museums, and remote manipulation of robotic grippers. One drawback of the design is a limitation on the tightness of the grip that can be achieved due to location of the actuators within the palm.

2.3.3 Tactile Interfaces

Tactile interfaces convey tactual information, that is, information related to heat, pressure, vibration, and pain. Just like the wide range of stimuli displayed by tactile interfaces, the interfaces themselves come in various designs with a variety of sensing and actuation technologies. Hence, classification of tactile interfaces is nearly impossible, and no single interface is representative of state of art in tactile interface design. Most tactile interfaces provide feedback to fingertips of the operator, although some interfaces intended for other parts of the body, like the back,

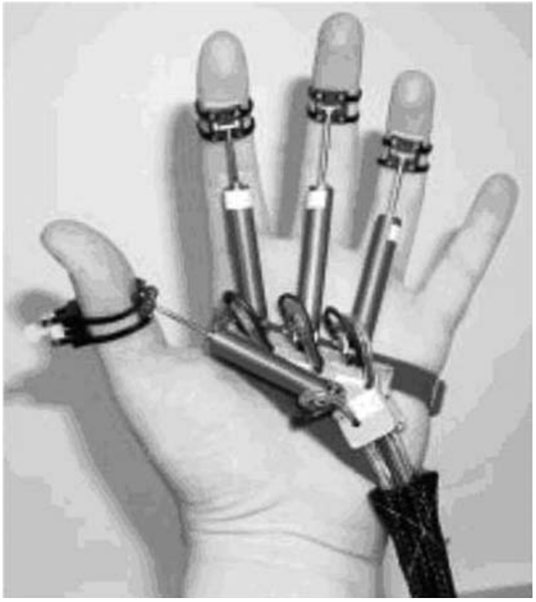

FIGURE 2.10

Rutgers Master II.
This hand master employs pneumatic actuators into the palm, thereby eliminating the need for a transmission. *Source*: From Bouzit et al. (2002).

have also been implemented. In this section, we take a look at vibrotactile displays, which are one of the most common forms of tactile interfaces, and tactile interfaces for the torso.

Vibrotactile Interfaces

These are tactile interfaces for conveying vibratory information to an operator. Applications where vibrotactile displays can be particularly useful include inspection tasks, texture perception, scientific data visualization, and navigational aids. Kontarinis and Howe (1995) were the first to present design guidelines for implementation of vibration displays. Based on the properties of the human tactile system, they noted that a vibration display device should produce mechanical vibrations in the range of 60 to 1000 Hz with variable amplitude and frequency. In order to achieve this goal, they employed modified 0.2-Watt loudspeakers. The complete setup is shown in Figure 2.11. The range of motion of the device is 3 mm, and it can produce up to 0.25 N peak force at 250 Hz. The user grasps the master manipulator as shown in the figure. Another similar robot manipulator, known as the slave, that has acceleration sensors mounted on its ends, sends

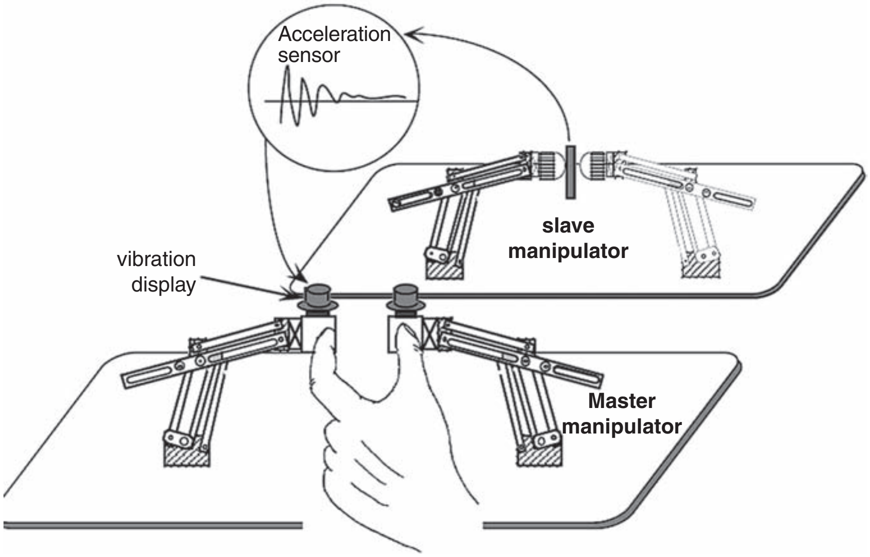

FIGURE 2.11 Loudspeaker-based vibrotactile display.
Vibrations are conveyed to human operator through brackets mounted at the end of the master manipulator. Subjects perform various tasks in a teleoperation setting. *Source*: From Kontarinis and Howe (1995).

back data related to the vibrations felt while grasping an object. These data are then displayed to the human operator.

Okamura and colleagues (2001) developed decaying sinusoidal waveform-based models for vibration feedback during haptic interaction. Through experiments performed with real materials, they recorded amplitude, frequency, and decay rates of vibrations during impact events. They noted that for some materials the parameters were beyond the bandwidth of their haptic display, and hence, the interface was not capable of displaying those vibrations. These authors reported that incorporation of vibration feedback along with force feedback led to improved performance during material discrimination tasks. Experiments were conducted using the 3GM haptic interface by Immersion Inc. Similar results were presented in Okamura et al. (1998) using the IE 2000 joystick, also by Immersion.

Wearable Tactile Interfaces

Most tactile interfaces are made for the fingertip, given its high perceptual sensitivity. However, given the small size of the fingertip, tactile interfaces for other parts of the body, including the torso (Ertan et al., 1998; Traylor & Tan, 2002) and the mouth (Tang & Beebe, 2006), have also been explored. The torso is primarily attractive as the surface area of skin on the back can convey twice the amount of information as the fingertips (Jones et al., 2004).

Tan and Pentland (1997) provide an overview of technologies for wearable tactile displays. The researchers also developed a directional haptic display, called the "rabbit," comprised of a 3 × 3 array of nine vibrotactile actuators for the back of a user. The device makes use of the "sensory saltation" phenomenon (Gerald, 1975) to provide directional information to the human user. If tactile cues are sequentially applied to three spatially separated points on the arm of a subject, then the actual perception of the subject is of the cues to be uniformly distributed over the distance between the first and the last tactile actuator. This spatial resolution of the discrete cues felt by the subject is also more than the spatial resolution of the applied cues themselves. This phenomenon is known as "sensory saltation," and allows researchers to achieve high spatial resolution with the use of few actuators.

In similar work, Jones and colleagues (2004) presented the design of a tactile vest using vibrotactile actuators for directional display of spatial information to the blind. The vest provided directional cues to the blind user through the tactile actuators mounted on the back. They evaluated and compared four different electrical actuators for the vibrotactile vest, and chose a pancake motor after considering peak frequency, power requirements, and size of the actuators. They found that the participants identified the directions 85 percent of the time, with most errors being in the diagonal direction. These results indicate that wearable tactile interfaces are promising candidates to serve as navigational aids for the disabled.

Jones and colleagues (2004) also built and tested a shape memory alloy (SMA)–based tactor unit for tactile feedback to the torso (Figure 2.12). The unit had an overall height of 17 mm, length of 42 mm, and width of 22 mm. In experiments, the tactor unit produced a peak force in the range of 5 to 9 N, with an average of 7 N with a displacement of 3 mm. The bandwidth of the tactors was less than 0.3 Hz. In experimental studies, tactors were arranged in 1 × 4 and 2 × 2 arrays, and activated sequentially as well as together. They noted that although the users perceived the stimulation, it was not well localized and felt like firm pressure such as a finger prodding the skin. Furthermore, stimulations on fleshier areas of the back were found to be more easily detectible than near the spinal cord. These experiments suggest that SMA tactors may be used for tactile feedback to the torso, which can lead to lighter, more compact vests due to better power-to-weight characteristics of SMA as compared to electrical actuators.

2.3.4 Applications of Interface to Accessibility

The modalities of both haptics and vision are capable of encoding and decoding important structural information on the way object parts relate to each other in a 3D world (Ballestero & Heller, 2006). Due to this similarity in the role of the haptic and visual modalities, engineers and researchers have been interested in the

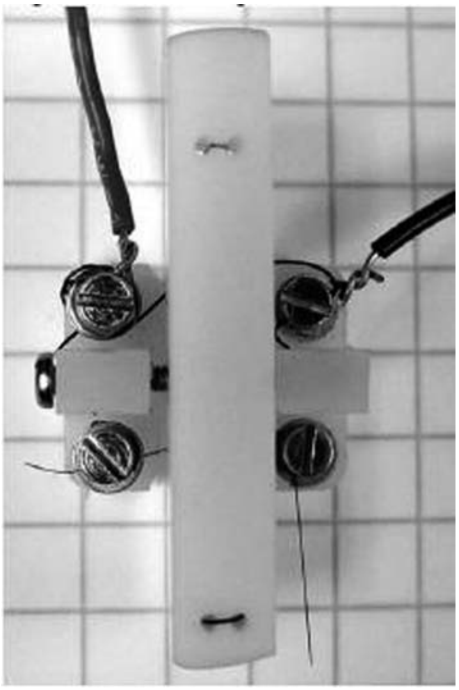

FIGURE 2.12 Single SMA tactor unit.
SMA-based vests have the potential to be lighter and more compact than vibrotactile ones. *Source*: From Jones et al. (2004).

use of touch in the absence of vision. The Tactile Vision Substitution System (TVSS) was, perhaps, one of the most dramatic early examples of this interest (Bach-y-Rita, 1972). The original TVVS employed a camera connected with a computer and an array of vibrating stimulators on the skin of the back. The basic idea was to allow people to "see" with their skin. A derivative of the TVVS was the Optacon, a portable tactile display to permit blind people to read printed material. The main unit of the Optacon contained a template or "array" with 144 tiny pins. The pins of the array vibrated to create a tactile image of alphabets and letters as camera lens was moved over them.

Recent advances in haptic interfaces have led to renewed research efforts to build haptic interfaces for the blind or visually impaired. There are three types of haptic interfaces for accessibility: devices like the Optacon that tactually display material to be read, haptic navigational aids for navigation without sight, and haptic interfaces for web or computer access. Christian (2000) provides a broad overview of haptic display design for blind users. He notes that even though little research has focused on the design of tactile displays for the blind, already the tactile displays outperform speech interfaces both in terms of speed and performance. Also, tactile displays, as compared to auditory ones, speak a universal language. They can be understood by any blind user, regardless of language.

Haptic Braille Displays

A Braille display is a device, typically attachable to a computer keyboard, which allows a blind person to read the textual information from a computer monitor one line at a time. Each Braille character consists of six or eight movable pins in a rectangular array. The pins can rise and fall depending on the electrical signals they receive. This simulates the effect of the raised dots of Braille impressed on paper. Several Braille displays are commercially available.

Pantobraille is a single-cell bidirectional Braille display developed at the Centre for Information Technology Innovation, Canada (Ramstein, 1996). A Braille module is coupled with the Pantograph, a planar haptic display. The device provides the user with a combination of tactile stimulation and strong feedback. It has a workspace of 10 cm × 16 cm and unlike traditional Braille displays, allows the reader to move over the material in a bidirectional fashion. In a pilot study with two users, Ramstein found that the users preferred the interface over the Optacon, even though no significant improvement in performance over large Braille displays was realized.

HyperBraille is another text screen-oriented application that integrates tools for creating, retrieving, and sharing printed and electronic documents (Kieninger, 1996). As compared to other similar tools that provide blind users access to specific applications, the HyperBraille system promotes the use of standard document formats and communication protocols. For example, various parts of a letter such as the sender, recipient, and body are pre-labeled, and HyperBraille automatically generates links to take the blind reader to those parts of the documents.

Haptic Access to Graphical Information

Unlike the Braille displays that provide textual information to the blind, some haptic interfaces provide blind users access to the elements of a regular GUI. An example of such a device is the Moose, a haptic mouse (O'Modhrain & Gillespie, 1997). The Moose, shown in Figure 2.13, is effectively a powered mouse that displays elements of a GUI using haptic cues. For example, window edges are represented by grooves, and checkboxes use attractive and repulsive force fields. Yuand colleagues (2000) have investigated the use of haptic graphs for data visualization in blind users. Based on experiments on blind and sighted users, they recommend the use of engravings and textures to model curved lines in haptic graphs. Furthermore, they propose the integration of surface properties and auditory cues to aid the blind user.

The previously mentioned interfaces allow exploration of a GUI in two dimensions. The Haptic and Audio Virtual Environment (HAVE) developed under the European Union GRAB project seeks to provide blind users access to 3D virtual environments. This is achieved by the means of a dual-finger haptic

FIGURE 2.13 Moose haptic interface.

The Moose reinterprets the Microsoft Windows screen for blind users. *Source*: From O'Modhrain and Gillespie (1997).

interface, as shown in Figure 2.14. The haptic display is further augmented with the use of audio input and output. Wood and colleagues (2003) evaluated the interface through a simple computer game for blind users and concluded that users can easily find and identify objects within the game, and can cause changes in the game environment and perceive them. In addition, all users improved quickly and reported an immersive experience.

FIGURE 2.14 Haptic and Audio Visual Environment.

HAVE provides a multimodal display for 3D exploration for blind users. The haptic interface is pictured. *Source*: From Wood, Magennis et al. (2003).

Haptic Navigational Aids

Haptic navigational aids, as the name implies, attempt to provide navigational information to blind users. As compared to auditory aids, the haptic signals provided by the haptic aids cannot be confused with environmental signals by the blind user. The two can also be used together to augment each other. Ertan and colleagues (1998) presented a wearable haptic guidance system that uses a 4 × 4 grid of micro-motors to tactually provide navigational information to a user's back. In addition to the tactile display, the proposed interface comprises an infrared-based system to locate the user in the environment and a computer for route planning. In similar work, a tactile vest (see Section 2.3.3) has been developed at the Massachusetts Institute of Technology (MIT) that provides navigational information to the user (Jones et al., 2004). The authors note that if the total area of the skin is considered, the torso can convey twice the amount of information of the fingertips. In more recent work, Tang and colleagues (2006) presented an oral tactile navigational aid for the blind (Figure 2.15).

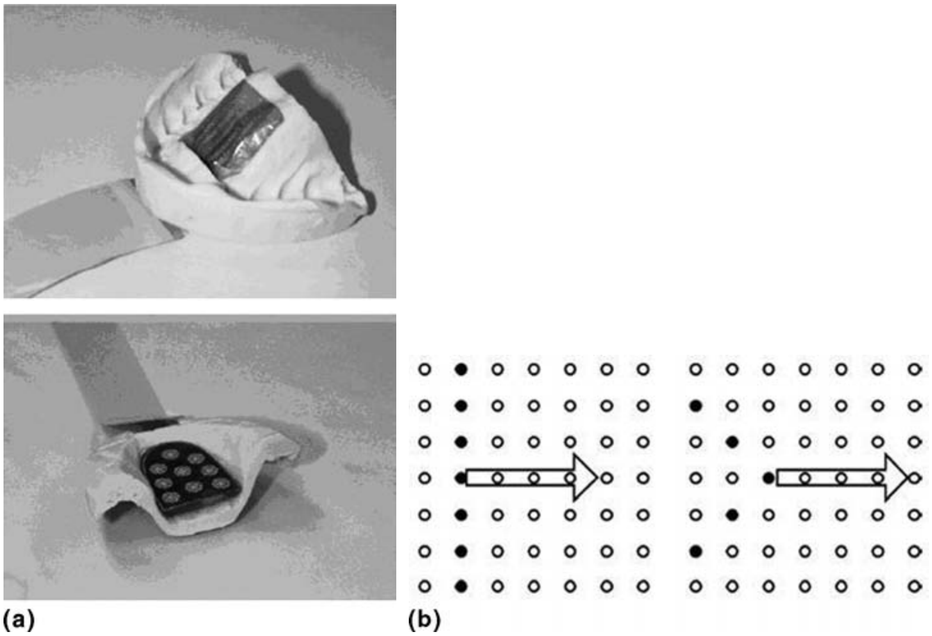

FIGURE 2.15 Oral navigational aid for the blind.
(a) Aid fits the upper teeth and tongue-touch keypad for the bottom (*left*).
(b) Moving lines and arrows are used to provide directional cues as shown on the right. *Source*: From Tang and Beebe (2006).

The device is a mouthpiece with a microfabricated electrotactile display to provide tactile information to the roof of the mouth. A tongue-touch keypad is provided for simultaneous operation. The device provides directional cues to the operator in four different directions—left, right, forward, and backward—using lines and arrows. In preliminary experiments, the researchers found that small electrical signals were sufficient for stimulating the roof of the mouth. In a preliminary experimental study, user performance was found to be good for discrimination of left and right signals, and mixed for the forward and backward ones.

2.4 HUMAN FACTORS DESIGN OF INTERFACE

There are two basic functions of haptic interfaces. First, the device is used to measure the motion (position, velocity, and possibly acceleration) and the contact forces of the user's entire body, or arm, foot, or hand. Second, the device is used to display contact forces and motion along with spatial and temporal distributions to the user (Tan et al., 1994). While current technology in haptic interfaces is limited, thereby allowing the display of only approximate interactions with a comparable real environment, the feedback experienced via a haptic device can feel very realistic, and can indeed improve human performance and sensations of realism when interacting with a virtual environment. These experiences are primarily attributed to the device's ability to exploit limitations of the human tactile and kinesthetic sensory channels. To specify a haptic interface for a given application, it is therefore necessary to understand the biomechanical, sensorimotor, and cognitive abilities of the human system (Tan et al., 1994). Sections 2.4.1 and 2.4.2 discuss the possible uses of haptic interfaces and the factors to be considered when selecting interfaces for a particular application, respectively. Section 2.4.3 is aimed at readers interested in designing and building their own interfaces.

2.4.1 When to Select a Haptic Interface

Haptic interfaces have a number of beneficial characteristics, such as enabling perception of limb movement and position, improving skilled performance of tasks (typically in terms of increased precision and speed of execution of the task), and enabling virtual training in a safe and repeatable environment. Force feedback has been shown, specifically for teleoperator systems, to improve performance of the operator in terms of reduced completion times, decreased peak forces and torques, and decreased cumulative forces and torques (Hill, 1979; Draper et al., 1987; Hannaford et al., 1991; Kim, 1991; Massimino & Sheridan, 1994; Murray et al., 1997; Williams et al., 2002; O'Malley & Ambrose, 2003). For training, virtual environments can provide a setting for safe, repeatable practice, and the inclusion of haptic feedback in such environments improves feelings of realism in the task, increasing the likelihood for skill transfer from the virtual to the real environment.

Haptic feedback is also shown to support hand–eye coordination tasks, specifically improving performance in dexterous manipulation (Hale & Stanney, 2004). Broadly speaking, haptic feedback can effectively alert people to critical tasks, provide a spatial frame of reference for the operator, and improve performance of tasks requiring hand–eye coordination (Hale & Stanney, 2004). Specifically tactile cues, such as vibrations or varying pressures applied to the hand or body, are effective as simple alerts, while kinesthetic feedback is key for the more dexterous tasks that humans carry out (Biggs & Srinivasan, 2002; Hale & Stanney, 2004).

Hale and Stanney (2004) provide an excellent summary of the benefits of adding tactile and kinesthetic feedback via diverse interface types, which are summarized here. First, they discuss texture perception. The addition of tactile feedback via a tactile display, in addition to visual feedback, results in more accurate judgment of softness and roughness compared to human performance of such tasks with visual feedback alone. If the tactile feedback is added to the visual display by means of a probe-based device rather than a tactile display, research shows that it is possible for the operator to judge softness and roughness with the same accuracy as when using the fingertip directly. Finally, if the tactile feedback is displayed to the operator via an exoskeleton device with tactile actuators in the fingertips, it is possible for the person to judge texture. Texture perception could be important in applications that involve exploration or object manipulation.

Tactile feedback can also be used to assist in two-dimensional (2D) form perception. For such tasks, visual feedback alone enables perception of the form's relative depth within the field of view. The addition of tactile feedback via a tactile display, either directly to the fingertip or through a probe device, does not do much to improve 2D form perception, and can be ignored, when irrelevant. For example, vibrotactile (binary) feedback added to visual feedback during a pick-and-place task does not significantly improve performance because the information is not rich enough for the operator (Murray et al., 1997). However, there is some benefit to having cross-modal cueing; for example, if tactile actuators are used within the fingers of an exoskeleton, it is possible to judge 2D form perception.

These researchers also summarize the benefits of adding kinesthetic feedback to visual displays for various tasks (Hale & Stanney, 2004). For the purpose of spatial awareness in terms of position (of objects in the environment or of self), visual displays alone enable comprehension of the relative depth of objects and visual proprioception within the field of view. The addition of kinesthetic feedback via a positional actuator further allows for an egocentric frame of reference within the operator's personal space, gestures for navigation of the environment, and target location (with less decay than visual target location). When using a probe-based device or an exoskeleton to provide kinesthetic feedback, the operator will experience enhanced distance judgments within the workspace. For example, perception of contact can be greatly improved with the use of haptic feedback over visual-only displays in situations where the viewing angle does not permit a clear view of the contacting points.

When the task is 3D form perception, visual feedback alone will result in identification and discrimination performance that is dependent on viewing angle, and the user will have no indication of the weight of objects in the environment. By including kinesthetic feedback via a probe-based system, the operator will experience deformability of objects in the environment through the force feedback, thereby aiding discrimination and identification. With an exoskeleton system, the user will experience improved weight discrimination of objects along with improved object interaction. This kind of information can be critical in applications like surgical training and telesurgery, where high manual dexterity is desired. For both probe-based and exoskeleton devices, the inclusion of haptic feedback to a visual virtual environment results in increased sensations of "presence" or embodiment within the virtual world.

Finally, haptic interfaces could be included to augment visual information. Examples of such applications include augmentation of a GUI (see Section 2.3.4), scientific data visualization, or CAD.

2.4.2 Data Needed to Build Interface

Upon determining that the inclusion of haptic feedback is beneficial to a virtual or remote environment display, a number of decisions must be made in order to build a haptic interface system, even if commercial hardware is to be selected. First, the designer must determine if tactile or kinesthetic feedback is preferred. These decisions are dependent on the type of feedback that the designer wishes to provide. For example, if the desire is to provide a simple alert to the user, or to display textures or surface roughness, then a tactile device is most appropriate. In contrast, if 2D or 3D shape perception, discrimination, or presence in the virtual or remote environment is the goal, then kinesthetic devices are preferred. Refer to Section 2.4.1 for a discussion of situations where haptic feedback might be beneficial.

If kinesthetic, then the designer must select a probe- or joystick-type device that is grasped by the user, or an exoskeleton device that is worn by the user. When selecting a desktop device versus a wearable exoskeleton device for kinesthetic force display, the designer must decide on the importance of mobility when using the interface, and the nature of the feedback to be displayed. Often, we choose to simulate interactions with an environment through use of a tool wielded in the hand, in which case the desktop devices are entirely suitable. Exoskeleton devices, on the other hand, enable joint-based feedback to simulate grasping of objects for hand exoskeletons, or manual object manipulation for the more complex exoskeletons.

For all applications, the designer must consider the perceptual elements of the application for which haptic feedback is to be designed. For example, does the user need to discriminate between two cues or just detect them? Is the feedback within human perceptual capabilities? Will the user be fatigued after prolonged use? Can the user discriminate among different vibratory cues provided? These factors are highly task dependent, and answering such questions for an array of possible applications is beyond the scope of this chapter. Designers are encouraged to read the literature for numerous examples of applications of haptic interfaces and to refer to Section 2.1.2 for a summary of human perceptual capabilities. Due to the wide range of applications for which haptic feedback may be desired, variations introduced by different robotic devices, parts of the body with which the device may interface, nature of feedback, the precise role of a cue in a particular application, and users, the designers may need to conduct their own experiments and user studies to fully answer some of these questions.

Kinesthetic Feedback Devices

For both probe-based and exoskeleton devices, the design decisions that must be made in order to implement the device are similar. Again, as with the nature of the feedback (tactile versus kinesthetic), decisions are often task dependent. The designer must determine an appropriate DOF number for the device—too few and the flexibility of the device will be compromised, while too many will overcomplicate the implementation. For example, is planar motion in the virtual environment sufficient, or does it require motion in three-dimensional space? It is also important to consider how many DOF the user requires, and how many DOF of force feedback are appropriate. For example, the popular PHANToM haptic devices (Sensable Technologies, Woburn, MA) allow for six DOF of motion control (three Cartesian motions and three rotations), while force feedback is provided only for the translational DOF, with limited detrimental effects on sensation of presence in the virtual environment by the user.

The size of the workspace is another significant design decision for any haptic device, and should be considered carefully. Scaling of operator motion from the device to the virtual environment, either to amplify operator motion or scale down motions if working in a microscopic environment, for example, is a feasible solution in many cases. It is not always necessary that motions with the haptic interface exactly mimic real-world tasks. However, if the application of the system is for training, then careful consideration of the workspace size and scaling should be practiced. Exoskeleton devices typically do not involve scaling of the user motion, except in some applications for upper extremity rehabilitation (Brewer et al., 2005). However, decisions about DOF and required workspace in terms of joint range of motion should be determined.

Decisions regarding the range of forces to be displayed by the haptic device are often directly coupled to workspace size and to the size and cost of the haptic interface hardware. Designers should consider the typical range of interaction forces that are required for the desired tasks to be rendered in the environment, but consideration of maximum human force output capabilities (to ensure user safety and reduce fatigue) along with knowledge of the limits of human force sensing capabilities for small forces (as presented in the section on human haptic sensing) will influence decisions. Designers should be careful to ensure that the selected device is capable of providing a quality of feedback that allows for successful task execution. For example, is a vibratory cue like that of a cell phone ringer all that is required, or should the user be able to discriminate between two separate cues?

Finally, the designer must implement the virtual environment via computer control of the haptic interface and (typically) a coupled visual and haptic display. Basic haptic rendering is not a focus of this chapter; however, the reader is referred to an excellent introduction to haptic rendering concepts presented by Salisbury and colleagues (2004).

Designers are strongly encouraged to review the commercially available haptic devices as their implementation will be more straightforward than building haptic devices for custom applications. As noted previously, there are a wide variety of devices available on the market with varying DOF and workspace dimensions. The remainder of this section focuses on additional decisions that must be made when fabricating a custom haptic interface.

When building a custom haptic interface, the designer must select the basic control approach for the system—impedance or admittance. Impedance devices will require sensors to record operator motions, and will be controlled by specifying the forces and torques that the environment will apply to the user based on his or her interactions. Such devices require mechanical designs that are very lightweight, stiff, and easily back-driveable. Admittance devices will require sensors to record operator forces, in addition to position sensors to allow for closed-loop position control of the device. Often these systems are non–backdriveable and exhibit properties of typical industrial robots due to the position control approach of display of the virtual environment. Most commercial haptic interfaces are of the impedance display type.

Tactile Feedback Devices

The specifications required for tactile feedback devices are fewer in number than those required for kinesthetic haptic devices. The designer must determine the body location for the tactile display. Typically, this is the finger pad of the operator, although tactile displays have also been developed for the torso (Tan & Pentland, 1997; Traylor & Tan, 2002). Most tactile feedback devices are pin arrays; therefore, the designer must specify the density of the pin array and the method of actuation for the pins. For example, if the pins are too close, the user may not be able to discriminate simultaneous cues from two adjacent pins, whereas if they are too far apart the cues may appear disjointed. Tactile arrays for the finger pad can be static, or can be coupled to mouse-like devices that allow translation in a plane. The designer must determine if this capability is required for the application. Finally, lateral skin stretch (in addition to, or in place of finger pad deflection normal to the skin surface) can generate very different sensations for the human operator (Hayward & Cruz-Hernandez, 2000). Again, the appropriateness of the method of feedback and the selection of actuators and mechanical design will be task-dependent, and designers are strongly encouraged to review commercially available solutions, along with other tactile display devices that have been presented in the literature.

2.4.3 Detailed Description of What Is Needed to Specify Such Interface for Use

The features of kinesthetic and tactile haptic interfaces are described separately in this section. Sensing and actuation is discussed specifically for kinesthetic haptic interfaces, since selection of components for these tasks is closely coupled to the mechanical design of such devices.

Mechanical Design of Kinesthetic Haptic Interface

The mechanical design of a haptic interface includes specification of the device DOF, the kinematic mechanism, and portability. The most prominent feature of a haptic interface is the number and the nature of the DOF at the active end or ends. The active end refers to the part of the robot that is connected to the body of the operator. At the active end, the hand holds the device or the device braces the body; otherwise, the interaction is unilateral (Hayward and Astley, 1996). The DOF that are actuated or active and others that are passive are also critical. For example, the PHANToM is a pen-based mechanism that has six DOF at the endpoint, but only three of these are actuated (Massie & Salisbury, 1994). Through the PHANToM haptic interface, an operator can explore a virtual environment in six DOF (three in translation and three in rotation), but receives force feedback only in the three translational DOF. The choice of DOF of a particular haptic interface depends primarily on the intended application. Haptic interfaces range from simple single-DOF devices built for research (Lawrence & Chapel, 1994) to a 13-DOF exoskeleton master arm for force-reflective teleoperation (Kim et al., 2005).

The choice of the mechanism for a haptic interface is influenced both by the application and the part of the body interfaced with. Robotic mechanisms can be serial or parallel. A serial mechanism is composed of a sequence of links connected end to end with one end of the resulting linkage connected to the ground (base) and the other being free. Serial mechanisms provide simplicity of design and control, but typically require larger actuators than parallel mechanisms. In addition, errors in the motion of links near the base of the robot are propagated to the end effector resulting in loss of precision. A parallel mechanism, on the other hand, contains closed loops of these linkages with two or more connections to ground. Parallel mechanisms offer high structural stiffness, rigidity, precision, and low apparent inertia, which are desirable for the display of high-fidelity virtual environments, but these mechanisms tend to have singularities, limited workspaces, and more complex control schemes than their serial counterparts.

Haptic interfaces apply forces to the human operator. As a result, equal and opposite forces act on the interface and need to be distributed in order to maintain force equilibrium. Based on the grounding of these feedback forces, haptic devices can be classified as nonportable (grounded) or portable (ungrounded). A grounded haptic device is affixed to a rigid base, transferring reaction forces to ground. An ungrounded haptic device is attached only to the operator's body, exerting reaction forces on the user at the point(s) of attachment. Most of today's haptic interfaces like pen-based haptic devices and joysticks are grounded.

Typically, ungrounded haptic interfaces are good at providing feedback such as grasping forces during object manipulation, and have workspaces that permit natural movement during haptic interactions but at the expense of design simplicity. Alternatively, grounded devices perform better when displaying kinesthetic forces to the user, like forces that arise when simulating static surfaces (Burdea, 1996). The workspace of a grounded device is limited by the manipulator's link lengths and joint limits, such as in common desktop interfaces like the PHANToM Desktop by Sensable Technologies (workspace: 6.4 in wide × 4.8 in high × 4.8 in deep) or the Impulse Engine 2000 by Immersion Corporation (workspace: 6 in × 6 in).

Some haptic interfaces, mostly exoskeleton-type interfaces, can be wearable. Examples of such interfaces include the Rutgers Master II force feedback glove (Bouzit et al., 2002), the Salford arm exoskeleton (Tsagarakis & Caldwell, 2003), the L-Exos force-feedback exoskeleton (Frisoli et al., 2005), and the MAHI arm exoskeleton (Gupta & O'Malley, 2006).

Sensing and Actuation

Sensing and actuation are critical components of a haptic interface. Section 2.1 presented the human sensory and sensory motor capabilities. An effective haptic interface needs to match these requirements through its sensors and actuators. For high-quality haptic display, the actuators of a haptic interface should have a high power-to-weight ratio, high force/torque output, and high bandwidth. The bandwidth of an actuator refers to the range of frequency of forces that can be applied with the actuator. In addition, the actuators should have low friction and inertia as these can mask small feedback forces thereby destroying the sense of realism. Sensors for haptic interfaces should have high resolution. Due to the difference in human tactile and kinesthetic sensing, tactile and kinesthetic displays typically employ different sets of sensors and actuators.

Kinesthetic interfaces may use electrical actuators, hydraulic actuators, or pneumatic actuators. Electrical actuators are currently the most used haptic actuators. These include DC motors (both brushed and brushless), magnetic particle brakes, and SMA. Specific trade-offs of these types of actuators are discussed in detail in the online case studies mentioned in Section 2.7.

High-resolution sensors for kinesthetic interfaces are readily available, and generally, noncontact optical encoders that measure position of a motor shaft are used. These encoders typically have a resolution of less than half a degree, which is sufficient for most applications. Another option for position sensing is noncontact rotary potentiometers that, like the rotary encoders, are placed in line with the actuator shafts.

Mechanical Design of Tactile Haptic Interface

Tactile feedback can be provided using pneumatic stimulation by using compressed air to press against the skin (Sato et al., 1991), vibrotactile stimulation by applying a vibration stimulus locally or spatially over the user's fingertips using voice coils (Patrick, 1990) or micropin arrays (Hasser & Weisenberger, 1993), or electrotactile stimulation through specially designed electrodes placed on the skin to excite the receptors (Zhu, 1988). In addition, single-stage Peltier pumps have been adapted as thermal/tactile feedback actuators for haptic simulations, such as in Zerkus et al. (1993). Recently, a tactile display using lateral skin stretch has also been developed (Hayward & Cruz-Hernandez, 2000). Sensing in tactile interfaces can be achieved via force-sensitive resistors (Stone, 1991), miniature pressure transducers (MPT) (Burdea et al., 1995), the ultrasonic force sensor (Burdea et al., 1995), and the piezoelectric stress rate sensor (Son et al., 1994). For a thorough survey of current technologies related to tactile interface design, see Pasquero (2006).

2.5

TECHNIQUES FOR TESTING THE INTERFACE

As with all interfaces, haptic ones need to be evaluated to ensure optimal performance. Sections 2.5.1 and 2.5.2 describe some of the special considerations that must be taken into account when testing and evaluating haptic interfaces.

2.5.1 Testing Considerations for Haptic Devices

The evaluation can focus on the hardware alone, or performance can be measured by testing human interaction with the environment. Hardware testing is required to determine the quality of force feedback achievable by the interface. This involves examination of the range of frequencies of forces the device can display and the accuracy with which those forces can be displayed. Testing of the machine is application independent, in which the capabilities of the devices themselves are measured and comparison among various devices is allowed. User-based testing is task dependent and carried out to study the perceptual effectiveness of the interface, which is important from a human factors point of view.

When testing the hardware, the procedures are fairly straightforward, and should simply follow best practices for experiment design, data collection, and data analysis, including statistical considerations. For tests involving human subjects, first it is important to follow governmental regulations for human-subject testing, often overseen by an Institutional Review Board. Second, a sufficient number of subjects should be enrolled and trials conducted for the results to have statistical significance. Third, and specifically for haptic devices, it is necessary to isolate only those sensory feedback modalities that are of interest in a given study. For example, often the haptic interface hardware can provide unwanted auditory cues due to the amplifiers and actuators that provide the force sensations for the operator. In such studies, it is often beneficial to use noise-isolating headphones or some other method of masking the unwanted auditory feedback. Similarly, if focusing on the haptic feedback capabilities of a particular device, it may be necessary to remove visual cues from the environment display, since in many cases of human perception the visual channel dominates the haptic channel.

2.5.2 Evaluating a Haptic Interface

Several approaches can be taken when evaluating a haptic interface. First, performance of the hardware can be assessed using human subject testing, usually via methods that assess human performance of tasks in the haptic virtual environment, or that measure the individual's perception of the qualities of the virtual environment. To this end, researchers have studied the effects of software on the haptic perception of virtual environments (Rosenberg & Adelstein, 1993; Millman & Colgate, 1995; Morgenbesser & Srinivasan, 1996). Morgenbesser and Srinivasan (1996), for example, looked at the effects of force shading algorithms on the perception of shapes.

It is also common to compare performance of tasks in a simulated environment with a particular device to performance in an equivalent real-world environment (Buttolo et al., 1995; West & Cutkosky, 1997; Richard et al., 1999; Shimojo et al., 1999; Unger et al., 2001). Work by O'Malley and Goldfarb (2001, 2005) and O'Malley and Upperman (2006) extended these comparisons to include performance in high- and low-fidelity virtual environments versus those in real environments, demonstrating that although performance of some perceptual tasks may not be degraded with lower-fidelity haptic devices, human operators can still perceive differences in quality of the rendered virtual environments in terms of the perceived hardness of surfaces. Such studies can give an indication of the extent to which a particular device and its accompanying rendered environment mimic real-world scenarios and enable humans to perceive the virtual environment with the same accuracy as is possible in the natural world.

Finally, performance can be assessed using typical measures and characteristics of quality robotic hardware. Primary requirements for a haptic system are the ability to convey commands to the remote or virtual plant and to reflect relevant sensory information, specifically forces in the remote or virtual environment, back to the operator. In essence, the dynamics of the device must not interfere with the interaction between the operator and environment. Jex (1988) describes four tests that a haptic interface should be able to pass. First, it should be able to simulate a piece of light balsa wood, with negligible inertia, friction, or perceived friction by the operator. Second, the device should be able to simulate a crisp hard stop. It should simulate coulomb friction, that is, the device should drop to zero velocity when the operator lets go of the handle. Finally, the device should be able to simulate mechanical detents with crisp transition and no lag.

In practice, performance of a haptic interface is limited by physical factors, such as actuator and sensor quality, device stiffness, friction, device workspace, force isotropy across the workspace, backlash, computational speed, and user's actions (hand grip, muscle tone). From the previous discussion, it is clear that there is a wide range of haptic devices both in terms of their DOF and applications, making the task of generating a common performance function particularly challenging.

Various researchers have attempted to design a set of performance measures to compare haptic devices independent of design and application (Ellis et al., 1996; Hayward & Astley, 1996), including kinematic performance measures, dynamic performance measures (Colgate & Brown, 1994) (Lawrence et al., 2000), and application-specific performance measures (Kammermeier & Schmidt, 2002; Kirkpatrick & Douglas, 2002; Chun et al., 2004). Additionally, when developing custom hardware, sensor resolution should be maximized, structural response should be measured to ensure that display distortion is minimized, and closed loop performance of the haptic interface device should be studied to understand device stability margins. Detailed discussion of the techniques necessary for measuring these quantities is beyond the scope of this chapter.

2.6 DESIGN GUIDELINES

This section provides guidance on how to effectively design a haptic interface that is both safe and effective in its operation.

2.6.1 Base Your Mechanical Design on Inherent Capabilities of Human Operator

Because the haptic device will be mechanically coupled to the human operator, it is important to ensure that the characteristics of the system, such as workspace size, position bandwidth, force magnitude, force bandwidth, velocity, acceleration, effective mass, accuracy, and other factors, are well matched to the human operator (Stocco & Salcudean, 1996). The design goals for the system, if based on the inherent capabilities of the human hand (or other body part using the display), will ensure a safe and well-designed system that is not overqualified for the job.

2.6.2 Consider Human Sensitivity to Tactile Stimuli

Sensitivity to tactile stimuli is dependent on a number of factors that must be considered. For example, the location of application of the stimuli or even the gender of the user can affect detection thresholds (Sherrick & Cholewiak, 1986). Stimuli must be at least 5.5 msec apart, and pressure must be greater than 0.06 to 0.2 N/cm^2 (Hale & Stanney, 2004). Additionally, vibrations must exceed 28 dB relative to a 1-microsecond peak for 0.4 to 3 Hz frequencies for humans to be able to perceive their presence (Biggs & Srinivasan, 2002).

2.6.3 Use Active Rather than Passive Movement

To ensure more accurate limb positioning, use active movement rather than passive movement of the human operator. Additionally, avoid minute, precise joint rotations, particularly at the distal segments, and minimize fatigue by avoiding static positions at or near the end range of motion (Hale & Stanney, 2004).

2.6.4 Achieve Minimum Force and Stiffness Display for Effective Information Transfer from Virtual Environment

When implementing the virtual environment and selecting actuator force output and simulation update rates, ensure that the minimum virtual surface stiffness is 400 N/m (O'Malley & Goldfarb, 2004) and minimum endpoint forces are 3 to 4 N (O'Malley & Goldfarb, 2002) to effectively promote haptic information transfer.

2.6.5 Do Not Visually Display Penetration of Virtual Rigid Objects

A virtual environment simulation with both visual and haptic feedback should not show the operator's finger penetrating a rigid object, even when the stiffness of the virtual object is limited such that penetration can indeed occur before significant forces are perceived by the operator (Tan, Eberman 1994). This is because when no visual feedback is available, people tend to fail to differentiate the deformation of the soft finger pad from movements of the finger joints.

2.6.6 Minimize Confusion and Control Instabilities

In multimodal systems, it is important to minimize confusion of the operator and limit control instabilities by avoiding time lags among haptic/visual loops (Hale & Stanney, 2004).

2.6.7 Ensure Accuracy of Position Sensing in Distal Joints

Serial linkages require that the distal joints have better accuracy in sensing angular position than proximal joints, if the accuracy of all joints is constrained by cost or component availability (Tan et al., 1994). This is because joint angle resolution of humans is better at proximal joints than at distal ones.

2.6.8 For Exoskeleton Devices, Minimize Contact Area at Attachment Points for Mechanical Ground

It is important to minimize contact area for ground attachment points because humans are less sensitive to pressure changes when the contact area is decreased (Tan et al., 1994).

2.6.9 Ensure Realistic Display of Environments with Tactile Devices

Note that a human operator must maintain active pressure to feel a hard surface after contact, and maintaining the sensation of textured surfaces requires relative motion between the surface and the skin (Hale & Stanney, 2004).

2.6.10 Keep Tactile Features Fixed Relative to Object's Coordinate Frame

It is important to maintain this fixed relative position for realistic perception of objects with a tactile display. This requirement translates to a need for high temporal bandwidth of the pins (imagine fast finger scanning) (Peine et al., 1997). Matching maximum finger speeds during natural exploration is a useful goal.

2.6.11 Maximize Range of Achievable Impedances

Because it is just as important for the haptic device to be light and back-driveable as it is for the device to be stiff and unyielding, it can be difficult to optimize design parameters for a specific hardware system. Therefore, it is recommended to generally achieve a broad range of impedances with the device (Colgate & Schenkel, 1997). Such a range can be achieved by carefully selecting robot configuration, defining geometric parameters, using transmission ratios, incorporating external dampers, or enabling actuator redundancy (Stocco et al., 2001). Specifically, techniques include lowering the effective mass of the device (Lawrence & Chapel, 1994), reducing variations in mass (Ma & Angeles, 1993; Hayward et al., 1994; Massie & Salisbury, 1994), designing a device such that it exhibits an isotropic Jacobian (Kurtz & Hayward, 1992; Zanganeh & Angeles, 1997), or adding physical damping (mechanical or electrical) to the system (Colgate & Schenkel, 1997; Mehling et al., 2005).

2.6.12 Limit Friction in Mechanisms

To reduce nonlinearities in the haptic device, limiting friction is important. If using impedance control techniques, minimal friction is key to back-driveability of the device as well. Friction can be limited through the use of noncontacting supports like air bearings or magnetic levitation, by incorporating direct drive-actuation techniques, or if transmissions are needed to achieve desired forces and torques, by selecting cable drives over gears or other transmission methods.

2.6.13 Avoid Singularities in Workspace

In certain parts of the workspace, the robot endpoint may lose (inverse kinematics singularity) or gain (forward kinematics singularity) a degree of freedom. For example, if a robot arm with revolute joints is fully stretched, then the endpoint of the robot loses a degree of freedom as it cannot be moved along the line connecting the joints. Similarly, for parallel mechanisms in certain configurations, it is possible that the endpoint gains a degree of freedom, that is, it can be instantaneously moved without affecting the actuated joints. Near workspace locations that exhibit inverse kinematics singularities, significantly high torques are required to move the robot in the singular direction. Near these points, even during free movement, the operator of a haptic interface would need to exert considerable forces to move, thereby reducing the realism of display. Conversely, at a forward kinematics singularity, it is possible to initiate endpoint motion with little force, which is especially detrimental for haptic interfaces as it is not possible to display any force to the operator at these locations. Hence, singularities in the robot workspace should be avoided.

2.6.14 Maximize Pin Density of Tactile Displays

Objects feel more realistic as the spatial density of the pins is increased, although this will be limited by the size of actuators selected. Vertical displacement of pins should be 2 to 3 mm while providing 1 to 2 N of force to impose skin deflections during large loads (Peine et al., 1997).

2.7 CASE STUDIES

Case studies for several haptic interfaces can be found at *www.beyondthegui.com*.

2.8 FUTURE TRENDS

The commercial applications of haptic and tactile displays have been simple and inexpensive devices, such as the vibrations of a cellular telephone or pager, or force feedback joysticks common to video games. Haptic interfaces, both kinesthetic and tactile displays, which have greater capability and fidelity than these examples, have seen limited application beyond the research lab. The primary barrier has been cost, since high-fidelity devices typically exhibit higher numbers of DOF, power-dense actuation, and high-resolution sensing. Wearable haptic devices, specifically wearable tactile displays, will also likely see increased demand from defense to consumer applications for the purpose of situational awareness, with developments in flexible materials that can be woven into fabric. Therefore, a prediction for the next 10 to 20 years is much greater accessibility to haptic devices in commercial applications as the price of improved sensor and actuator technology comes down. Such widespread applicability of haptic interface technology, especially in gaming, will be catalyzed by the recent increase in video games that encourage and even require active human intervention (e.g., Dance Dance Revolution, Wii).

The second driver of haptic device proliferation will be the sheer number of applications where haptic feedback will prove itself beneficial. Improved data visualization by use of haptic (including kinesthetic and tactile) displays that enable increased channels of information conveyance to the user will be realized. Haptic devices are already under development in geoscience and pharmaceutical research and testing via haptic-enriched protein docking displays (Salisbury, 1999; Fritz & Barner, 1999). The most likely discipline for widespread adoption of haptic technologies will be medicine. From robotic-assisted rehabilitation in virtual environments with visual and haptic feedback, to surgical robotics that enable realistic touch interactions displayed to the remote surgeon, to hardware platforms that due to their reconfigurability and flexibility will enable new discoveries in cognitive neuroscience, to the incorporation of haptic sensory feedback in prosthetic limbs for the increasing population of amputees, haptic devices will enable a new dimension of interaction with our world.

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