Multimedia Contents

Haptics

42. Haptics

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The word *haptics*, believed to be derived from the Greek word *haptesthai*, means *related to the sense of touch*. In the psychology and neuroscience literature, haptics is the study of human touch sensing, specifically via *kinesthetic* (force/position) and *cutaneous* (tactile) receptors, associated with perception and manipulation. In the robotics and virtual reality literature, haptics is broadly defined as real and simulated touch interactions between robots, humans, and real, remote, or simulated environments, in various combinations. This chapter focuses on the use of specialized robotic devices and their corresponding control, known as *haptic interfaces*, that allow human operators to experience the sense of touch in remote (teleoperated) or simulated (virtual) environments.

Haptic technology is intimately connected with robotics through its reliance on dexterous mechatronic devices and draws heavily on the theoretical foundations of manipulator design, actuation, sensing, and control. In this chapter, we begin with motivation for haptic interface design and use, including the basic design of a haptic interface, information about human haptics, and examples of haptic interface applications. Next, we review concepts in the mechatronic design of kinesthetic haptic interfaces, including sensors, actuators, and mechanisms. We then examine the control aspect of kinesthetic haptic interfaces, particularly the rendering of virtual environments and stable and accurate display of forces. We next review tactile displays, which vary widely in their design due to the many types of tactile information that can be presented to a human operator. Finally, we provide resources for further study of haptics.

42.1 Overview

Haptics is the science and technology of experiencing and creating touch sensations in human operators. Imagine trying to button a coat, shake someone's hand, or write a note without the sense of touch. These simple tasks become extremely difficult to perform without adequate haptic feedback. To improve human operator performance in simulated and teleoperated environments, haptic interfaces seek to generate a compelling sensation that the operator is directly touching a real environment.

Haptic interfaces attempt to replicate or enhance the touch experience of manipulating or perceiving a real environment through mechatronic devices and computer control. They consist of a haptic device (HD, a manipulandum with sensors and actuators) and a control computer with software relating human operator inputs to haptic information display. While the low-level design of haptic interfaces varies widely depending on the application, their operation generally follows the *haptic loop* shown in Fig. 42.1. First, the haptic device *senses* an operator input, which may be position (and its derivatives), force, muscle activity, etc. Second, the sensed input is applied to a virtual or teleoperated environment. For a virtual environment, the effect of the operator's input on virtual objects and the subsequent response to be displayed to the operator are computed based on models and a *haptic rendering* algorithm. In teleoperation, a manipulator that is remote in space, scale, or power attempts to track the operator's input. When the manipulator interacts with its real environment, haptic information to be relayed to the operators is recorded or estimated. Finally, *actuators* on the haptic device are used to physically convey touch sensations to the human operator. Based on the haptic feedback, whether through unconscious or conscious human control, or simply system dynamics, the operator input is modified. This begins another cycle of the haptic loop.

Despite the simplicity of the concept of haptic display, there exist many challenges to developing compelling haptic interfaces. Many of these are addressed through fundamental robotics theory and an understanding of human haptic capabilities. In general, haptic interface performance specifications are based on human sensing and motor control characteristics. One major challenge in artificially generating haptic sensations is that the human operator's motion should be unrestricted when there is no contact with a virtual or remote object. Haptic devices must allow the human operator to make desired motions, thus requiring back-drivability and sufficient degrees of freedom of motion. A variety of robotic designs are used in haptic devices, including exoskeletons, actuated grippers, parallel and serial manipulators, small-workspace *mouse*-like devices, and large-workspace devices that capture whole arm, and even whole body, movement. Another challenge is that humans integrate kinesthetic (force/position) and cutaneous (tactile) information with motion and control cues to form haptic perceptions. Haptic devices would ideally include both force and tactile displays, although this has been rarely done due to size and weight limitations of actuators. Because of the human's sensitivity to high-frequency information, for many haptic interfaces and applications, this loop must repeat at a high

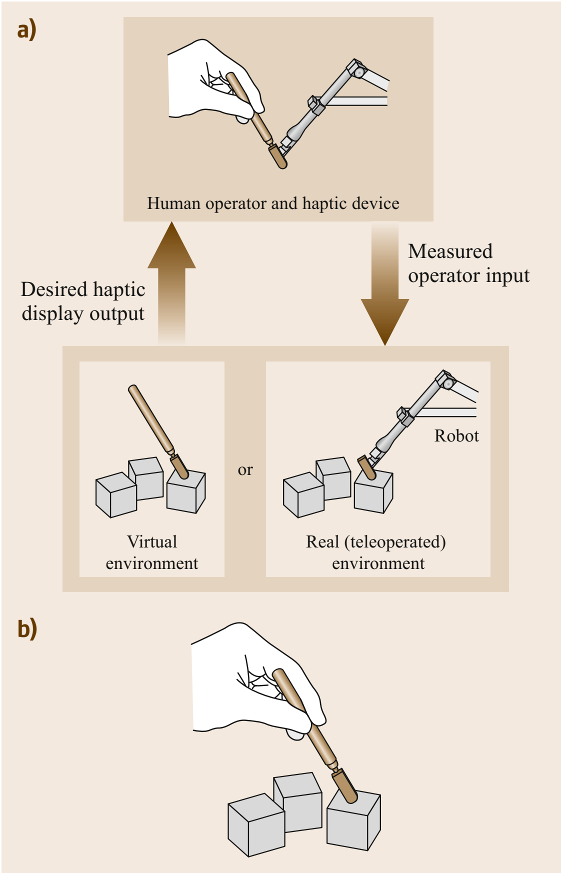

Fig. 42.1 (a) The *haptic loop* of a generic haptic interface. A haptic device senses human operator input, such as position or force, and the system applies this input to a virtual or teleoperated environment. The response of the environment to be relayed to the human operator is computed through models, haptic rendering, sensing, and/or estimation. Finally, actuators on the haptic device display corresponding touch sensations to the human operator. **(b)** The ideal result is that the human operator feels that he or she is interacting directly with a real environment

frequency, typically 1 kHz. Not only does a high update rate provide realistic (nondiscretized) touch sensations to the human operator, it also typically helps to maintain system stability. Controls analysis for haptic devices must consider both the continuous nature of the physical dynamics and the discrete nature of the computer control.

Before we examine the various components of haptic interfaces in detail, it is useful to motivate their design through a review of human haptics and applications of haptics. The remainder of this section is devoted to those topics.

42.1.1 Human Haptics

Two functions of the human nervous system play a primary role in haptics: kinesthesia (the internal sensing of forces and displacements inside muscles, tendons, and joints), and tactile sensing (the sensation of deformations of the skin).

Anatomy and Physiology

Haptics incorporates both, and is associated with an activity such as manipulation or exploration. Most of this chapter will address systems meant to interact primarily with the kinesthetic modality. Devices specifically aimed at tactile perception are described in Sect. 42.5. Even if tactile stimuli are not explicitly generated by a haptic device, tactile receptors are still stimulated, and are known to respond to frequencies as high as 10 000 Hz [42.1] and displacements as small as 2–4 µm [42.2–4].

Kinesthesia is mediated by muscle spindles, which transduce stretch of muscles, and Golgi tendon organs, which transduce joint rotation, especially at the extremes of motion. In principle, these and similar receptors could be stimulated directly to produce haptic sensations. For example, a vibration applied to a muscle tendon creates a strong sensation of muscle lengthening and corresponding joint motion in humans [42.5, 6]. Research in peripheral nerve stimulation for prosthesis control has demonstrated that electrodes implanted within individual fascicles of peripheral nerve stumps in amputees can be stimulated to produce sensations of touch or movement referred to the amputee's phantom hand [42.7].

Psychophysics

At the next level up from physiology and anatomy, psychophysics [42.8], the science of the physical capabilities of the senses, has been a rich source of design data for haptic device development. Its chief contribution has been methodologies that haptics researchers have applied to answer questions about what capabilities are needed in haptic devices. These sensory capabilities could then be translated into design requirements. Some of the chief psychophysical methods that have been fruitfully applied to haptics include threshold measurement by the method of limits and adaptive up-down methods. However, perception at threshold is not 100% reliable. Perception accuracy tends to depend on the strength of the stimulus, and the tradeoff between hit rate and false alarms depends strongly on the probability that a stimulus will be present in a given time interval (P_{stim}).

A more general notion is the receiver operating curve (Fig. 42.2, borrowed by psychophysics from radar theory), which plots the probability of a subject response given the existence of a stimulus, versus the probability of response given no stimulus. The curve is generated by measuring both probabilities at several different values of P_{stim}. The ideal response is the point (0,1): 100% response for stimuli and 0% response for nonstimuli. Human response is near this point for stimuli much above threshold, but declines to a rounded curve and eventually the 45° line as response below threshold becomes equal to chance.

Another relevant concept from psychophysics is the just noticeable difference (JND), commonly expressed as a percentage. This is the magnitude of a relative change in a stimulus, such as a force or displacement applied to the finger that is just perceivable by subjects.

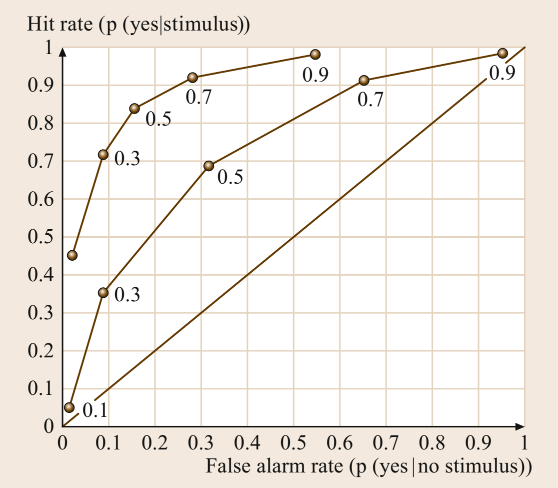

Fig. 42.2 Receiver operating curve (ROC). The ROC encodes the tradeoffs made by a subject between risk of false alarm and risk of missing a valid stimulus. Each point encodes a specific tradeoff between these two risks observed when stimuli are presented with a specified probability. ROCs for stronger signals tend towards the upper left hand corner (after [42.8] with permission from Lawrence Erlbaum and Associates, Mahwah)

For example, *Jones* [42.9] has measured JNDs of 6% for force applied to the human finger over a range of 0.5–200 N.

Psychology: Exploratory Procedures

In influential research starting in the 1980s, *Lederman* and *Klatzky* defined stereotyped hand motions called *exploratory procedures* (EPs), which are characteristic of human haptic exploration [42.10–12]. They placed objects into the hands of blindfolded subjects, and videotaped their hand motions. Their initial experiments [42.11] showed that the EPs used by subjects could be predicted based on the object property (texture, mass, temperature, etc.) that the subjects needed to discriminate. They also showed that the EPs chosen by subjects were the ones best able to discriminate that property. Furthermore, when asked to answer specific questions about objects (*Is this an eating utensil, further a fork?*), subjects used a two-stage sequence in which a more general lifting EP preceded more specific EPs [42.12].

Lederman and Klatzky's eight EPs (Fig. 42.3) and the property for which they are optimal are:

1. Lateral motion (texture)
2. Pressure (hardness)
3. Static contact (temperature)
4. Unsupported holding (weight)
5. Enclosure (global shape, volume)
6. Contour following (exact shape, volume)
7. Part motion test (part motion)
8. Function testing (specific function).

Each of these EPs is a bimanual task involving contact with all interior surfaces of the hand, motion of the wrist and various degrees of freedom of the hand, and tactile and temperature sensors in the skin (e.g., EPs 1 and 3), and kinesthetic sensors in the arm (EP 4). A haptic device capable of supporting all of these EPs is far beyond today's state of the art. However, the significance of these results for the design of haptic interface is great, since they allow us to derive device requirements from EPs.

42.1.2 Application Examples

The most common haptic device encountered by the general population is a vibration display device that provides haptic feedback while an operator plays a video game. For example, when the operator drives off the virtual road or bumps into a virtual wall, the hand controller shakes to imply driving over a rough surface or displays an impulse to represent the shock of hitting a hard surface. We examine two more pragmatic examples, medical simulators and computer-aided design (CAD) systems, in detail below. In addition, we review several commercially available haptic devices. Although haptic interfaces are not yet in widespread commercial use outside of entertainment, they are being integrated into numerous applications where the potential benefits are clear enough to justify the adoption of new technologies. A variety of novel and creative applications are being developed regularly in numerous fields, including:

- Assistive technology
- Automotive
- Design
- Education
- Entertainment
- Human–computer interaction
- Manufacturing/assembly
- Medical simulation
- Micro/nanotechnology
- Molecular biology
- Prosthetics
- Rehabilitation
- Scientific visualization
- Space
- Surgical robotics.

Medical Simulations

A major example driving much of today's haptic virtual environment research is simulation for training of hands-on medical procedures. Medical invasive thera-

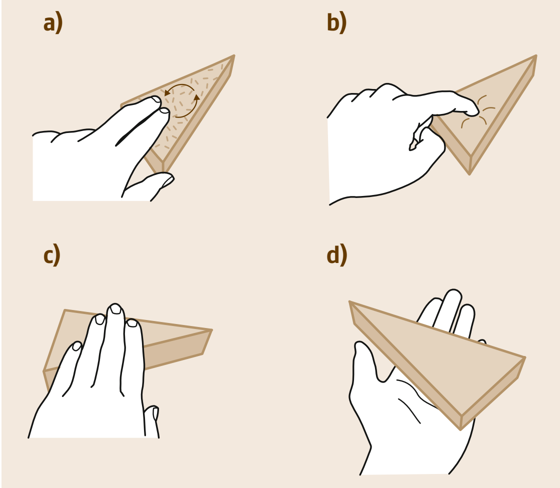

Fig. 42.3a–d Four of the eight human exploratory procedures (EPs). **(a)** Lateral motion (texture); **(b)** pressure (hardness); **(c)** static contact (temperature); **(d)** unsupported holding (weight) (after *Lederman* and *Klatzky* [42.11])

peutic and diagnostic procedures, ranging from drawing blood samples to surgery, are potentially dangerous and painful for the patient and require the student to learn hands-on skills mediated by haptic information pathways [42.13]. Simulators both with and without haptic feedback aim to replace supervised learning directly on human patients or on animals. Simulators have proven highly effective in developing minimally invasive surgery skills [42.14], especially when haptic feedback is provided in early training [42.15]. Expected benefits of training with haptic simulators include:

- Reduced risk to patients both during and immediately after training
- Increased ability to simulate unusual conditions or medical emergencies.
- Ability to collect physical data during the training process and provide specific and directed feedback to the student.
- Increased training time per unit of instructor effort.

Approaches for simulator designs, specific medical applications, and training evaluation methods have also been widely studied in the last two decades, e.g., [42.16, 17]. However, the costs of this technology are still high. In addition, it is not always clear which improvements in simulator technology, such as haptic device performance or accuracy of soft-tissue modeling, lead to improved clinical performance and, ultimately, patient outcomes.

Computer-Aided Design

The Boeing Company [42.18] has studied the use of haptic interfaces for solving advanced problems in CAD. One such problem is verification of the ability to efficiently maintain a complex system such as an aircraft. In the past, mechanics could verify the procedures (such as change-out of parts) on a physical prototype. However, this analysis is difficult or impossible to perform visually on an advanced CAD system. The VoxMap Pointshell system (Fig. 42.4) was developed to allow test extraction of parts with a haptic interface. Force sensations from the haptic interface reproduce for the operator the physical constraints of the part bumping into elements of the complex workplace. If the operator can remove the part in the haptic interface, it is verified that this part can be maintained without undue disassembly of the aircraft. This capability has been proved useful in actual design activities.

Commercially Available Haptic Devices and Systems

There are a wide variety of haptic devices available from companies, although many researchers build their own haptic devices for special purposes. At the time of this writing, one of the most popular commercially available haptic devices is the Geomagic Touch [42.19], formerly known as the Phantom Omni from SensAble Technologies (Fig. 42.5). In the 1990s and 2000s, SensAble developed the Phantom line of stylus-type haptic devices. The Phantom Premium [42.20], a higher fidelity, larger workspace device, has also been used widely in haptics research. The high price of haptic devices (compared to visual displays) restricts the development of some commercial applications. The Geomagic Touch (Phantom Omni), which is an order of magnitude less expensive than the Phantom Premium, has gained popularity among haptics and robotics re-

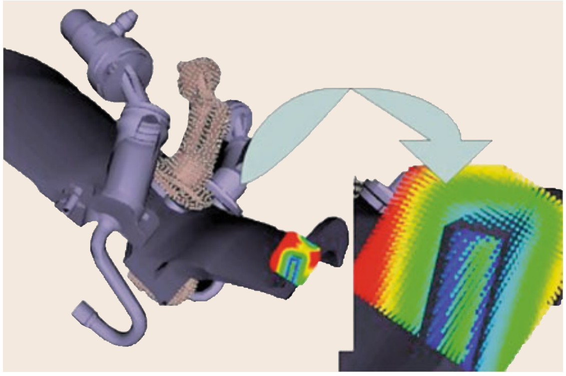

Fig. 42.4 Boeing computer-aided design (CAD) application for assembly and maintenance verification of complex aircraft systems. Boeing researchers developed the Voxmap/Pointshell software for haptically rendering very complex models in six degrees of freedom at high rates (courtesy of Bill McNeely, Boeing Phantom Works)

Fig. 42.5 The Phantom Omni device from SensAble Technologies, now marketed as the Geomagic Touch. This relatively low-cost device senses motion in six degrees of freedom from the stylus and can apply forces in the x, y, and z directions to the stylus tip (courtesy SensAble Technologies, Inc., Woburn)

searchers. In 2007, Novint Technologies [42.21] released the Novint Falcon, an inexpensive 3-DOF (three-degree-of-freedom) haptic device that is in turn an order of magnitude less expensive than the Phantom Omni.

Immersion has aimed at the mass market and consumer segments with a wide variety of haptics-based products, many of them involving a single degree of freedom. For example, they have licensed technology to makers of various video games, as well as mobile phone manufacturers, in the form of vibratory feedback in handheld devices and haptic-enabled steering wheels for driving games. Immersion also has a medical division selling medical simulators with haptic feedback.

Software for haptic rendering has also become widely available, through both commercial sources and research groups. Most companies that sell haptic devices also provide a standard development kit (SDK) with haptic rendering capability. In addition, not-for-profit open-source projects such as Chai3D [42.22] aim to make rendering algorithms from different groups publicly available, shortening application development time and allowing direct comparison of algorithms for benchmarking purposes.

42.2 Haptic Device Design

There are two broad classes of haptic devices: *admittance* and *impedance* devices. Admittance devices sense the force applied by the operator and constrain the operator's position to match the appropriate deflection of a simulated object or surface in a virtual world. In contrast, an impedance haptic device senses the position of the operator, and then applies a force vector to the operator according to computed behavior of the simulated object or surface.

Robots of the impedance type are back-drivable, have low friction and inertia, and have force-source actuators. A commonly used impedance haptic device in robotics-related research is the Phantom Premium [42.20, 23]. Robots of the admittance type, such as typical industrial robots, are non-back-drivable and have velocity-source actuators. The velocity is controlled with a high-bandwidth low-level controller, and is assumed to be independent of applied external forces. Some commercially available haptic devices, such as the HapticMaster [42.24], do operate under admittance control. While such closed-loop force control has been used for haptic display, more commonly designers have opted for mechanisms specially designed for open-loop force control to achieve simultaneously low cost and high bandwidth.

The choice of admittance or impedance architecture has many profound implications in the design of the software and hardware system. For a variety of reasons, including cost, the majority of haptic devices implemented today are of the impedance type. Because the preponderance of systems today are impedance devices and limitations on space, we limit our subsequent discussion to that class.

42.2.1 Mechanisms

Creating high-fidelity haptic sensations in the operator requires attention to mechanism design (Chap. 5). The requirements for impedance haptic devices are similar to those for designing manipulators suitable for force control. Desirable mechanism attributes for open-loop force control include low inertia, high stiffness, and good kinematic conditioning throughout a workspace designed to effectively match the appropriate human limb, primarily the finger or arm. The weight of the mechanism should be minimized, as it is perceived by the operator as weight and inertia of the virtual or teleoperated environment. Kinematic singularities (Chaps. 2, 5, and 18) are detrimental to haptic interfaces because they create directions in space in which the end-point cannot be moved by the human operator and thus impose disturbances on the illusion of haptic contact with virtual objects. High transmission ratios must be avoided as they introduce significant amounts of friction. This constraint requires haptic interfaces to make high demands on actuator performance.

Measures of Mechanism Performance

The ideal haptic device can move freely in any direction and is free of singular configurations as well as the *bad* effects of operating in their neighborhood. Traditionally, kinematic performance has been derived from the mechanism's Jacobian matrix, $\mathbf{J}(p,q)$, using some of the following well-known measures:

- Manipulability [42.25]: the product of the singular values of $\mathbf{J}(p,q)$
- Mechanism isotropy [42.26]: the ratio of smallest to the largest singular value of $\mathbf{J}(p,q)$
- Minimum force output [42.25, 27, 28]: maximizing the force output in the *worst* direction.

Dynamics can also be introduced into the cost function using measures such as dynamic manipulability [42.29]. This is still an active area of research and there is no consensus yet on which dexterity measure is most appropriate for haptic devices.

Kinematic and Dynamic Optimization

This aspect of design requires synthesis of mechanisms that match the workspace of the (most often) human finger or arm while simultaneously avoiding kinematic singularities.

A haptic device workspace is defined to match that of the targeted human limb. This can be assisted by the use of anthropometric data [42.30]. The performance goals, such as low inertia and avoidance of kinematic singularities, must be formalized into a quantitative performance measure which can be computed for any candidate design. Such a measure must account for:

- Uniformity of kinematic conditioning throughout the target workspace
- Favoring designs with lower inertia
- Guaranteeing that the target workspace is reachable.

The measures of mechanism performance defined above operate at a single point in space and thus must be integrated over the entire workspace to derive a figure of merit for a proposed haptic device design. For example, if S is the set of all joint angles Θ, such that the end effector is inside the target workspace, one such measure is

$$M = \min_S W(\Theta) , \quad (42.1)$$

where $W(\Theta)$ is a measure of design performance. The performance measure should include a link length penalty such as

$$M = \min_S \frac{W(\Theta)}{l^3} , \quad (42.2)$$

in order to avoid solutions which have excessive size, compliance, and mass of long links. We could search a large family of mechanism designs to maximize M. For example, if a design has five free parameters (typically link lengths and offsets), and we study ten possible values for each parameter, 10^5 designs must be evaluated.

Available computing power has grown much faster than the complexity of realizable mechanisms on the human scale (as measured by their DOF). Thus, brute-force search of design spaces is often sufficient, and sophisticated optimization techniques are not necessary.

Grounded Versus Ungrounded Devices

Most current devices that provide kinesthetic feedback are physically grounded, that is, forces felt by the operator are with respect to the operator's *ground*, such as the floor or desktop. Ungrounded haptic feedback devices are more mobile and can operate over larger workspaces compared to grounded devices, which enables them to be used in large-scale virtual environments. A number of ungrounded kinesthetic feedback devices have been developed, for example [42.31–33]. Comparisons have been made between the performance of ungrounded and grounded haptic displays [42.34]. Some ungrounded devices provide tactile rather than kinesthetic sensations, and these are described in Sect. 42.5.

42.2.2 Sensing

Haptic devices require sensors to measure the state of the device. This state may be modified by the operator's applied position/force, the haptic control law, and/or device and environment dynamics. The operator's input is sensed in the form of an applied position or an applied force. Sensing requirements for haptics are similar to those of other robotic devices (Chap. 29) so only haptics-specific sensing issues are discussed here.

Encoders

Rotary optical quadrature encoders are typically used as position sensors on the joints of haptic devices. They are often integrated with rotary motors, which serve as actuators. The underlying sensing mechanism for encoders is described in Sect. 29.1. The required resolution of an encoder for a haptic device depends on the ratio between the angular distance of a single encoder tick to the end-point motion in Cartesian space. The resolution of the selected position encoder has effects beyond simple spatial resolution of the endpoint, including the maximum stiffness that can be rendered (Sect. 42.4) without unstable or nonpassive behavior [42.35].

Many haptic applications, such as the rendering of virtual environments with damping (in which force is proportional to velocity), require velocity measurement. Velocity is typically obtained by numerical differentiation of the position signal obtained by an encoder. An algorithm for velocity estimation must be selected which is free of noise but minimizes phase lag at the frequencies of interest [42.36]. Thus, an alternative method is to use specialized hardware that measures the time between encoder ticks in order to compute the velocity [42.37].

Force Sensors

Force sensors are used in haptic devices as the operator input to an admittance-controlled device, or as a mechanism for canceling device friction and other undesirable dynamic properties in an impedance-controlled device.

When a force sensor such as a strain gauge or load cell measures the operator's applied force, care must be taken to thermally isolate the sensor, since thermal gradients in the sensor caused by body heat can affect force readings.

42.2.3 Actuation and Transmission

Haptic devices are differentiated from traditional computer input devices by actuators that are controlled to provide appropriate haptic sensations to the human operator. The performance of the haptic device depends heavily on the actuator properties and the mechanical transmission between the actuator and the haptic interaction point (HIP).

Requirements for Haptics

The primary requirements for actuators and mechanical transmission in impedance-type haptic devices are: low inertia, low friction, low torque ripple, backdriveability, and low backlash. In addition, if the design is such that the actuator itself moves as the user's position changes, a higher power-to-weight ratio is desired. Although closed-loop force control has been used for haptic display in impedance devices, most often the mechanism is designed to have sufficiently low friction and inertia so that open-loop force control is accurate enough.

One common mechanical transmission for haptic devices is the capstan drive (Fig. 42.6), which consists of smooth cables wrapped around pulleys of differing diameter to provide a gear ratio. A no-slip, high-friction contact between the cable and the pulleys is maintained through several wraps of the cable. The capstan drive minimizes friction forces felt by the human operator because it prevents translational forces on motor and joint axes.

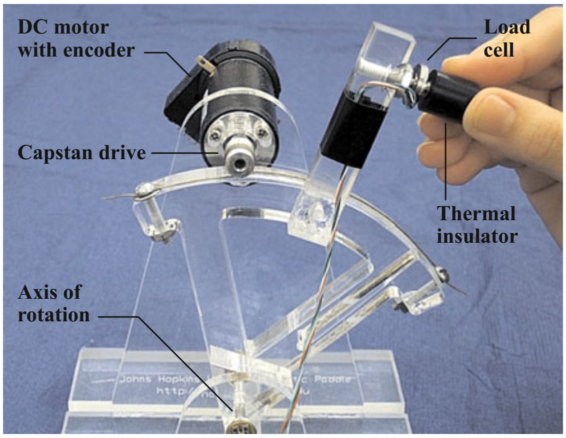

Fig. 42.6 This version of the Haptic Paddle [42.38] includes an encoder for position sensing, a single-axis load cell for force sensing, and a brushed motor with capstan transmission for actuation

Current amplifiers are typically used to create a direct relationship between the voltage output by the computer via a digital-to-analog (D/A) converter and the torque output by the motor. The effect of actuator and amplifier dynamics and D/A resolution on system stability is typically negligible in comparison to position sensor resolution and sampling rate for most haptic devices. Actuator or amplifier saturation can produce undesirable behavior, particularly in multi-DOF haptic devices where a single saturated motor torque may change the apparent geometry of virtual objects. The force vector, and thus the corresponding actuator torques, must be scaled appropriately if any actuator is saturated.

42.2.4 An Example Device

As an illustrative example, we will provide detailed design information for a simple 1-DOF haptic device known as the Haptic Paddle [42.38]. This section is meant to provide a concrete description of the types of components that are used in kinesthetic haptic devices, and the device can also be constructed following the instructions provided by Johns Hopkins University. Many widely available haptic devices share the common working principles of this device and differ chiefly in kinematic details arising from a greater number of DOF.

The haptic paddle shown in Fig. 42.6 is equipped with two sensors: a position a position encoder and a force sensor. A 500-counts-per-turn Hewlett-Packard HEDS 5540 encoder that is mounted directly on the motor. The quadrature process yields 2000 counts per revolution; the capstan transmission gear ratio and lever arm result in a position resolution of 2.24×10^{-5} m at the haptic interaction point (HIP). An optional load cell is used to measure the applied operator force. A plastic cap thermally insulates the load cell. In this device, the load cell can be used to minimize the effect of friction through a control law that attempts to zero the applied operator force when the HIP is not in contact with a virtual object.

The Haptic Paddle shown uses a brushed DC (direct current) motor with an aluminum pulley attached to the shaft. Like many commercial haptic devices, it uses a capstan drive: a cable is wrapped several times around the motor pulley and attached at each end of the large partial pulley. In one instantiation, the output of the digital-to-analog (D/A) converter from the microprocessor is passed through a current amplifier that gives a current through the motor that is proportional to the D/A voltage. This gives direct control of applied torque on the motor. The resulting system has a force felt at the driving point that is proportional to the output voltage during static operation. When the system is moving, the force applied to the operator may differ due to human and device dynamics.

42.3 Haptic Rendering

Haptic rendering (in impedance systems) is the process of computing the force required by contacts with virtual objects based on measurements of the operator's motion. This section describes haptic rendering for virtual environments. Haptic feedback for teleoperators is described in Chap. 43.

An important property of haptic systems is that their timing constraints are quite severe. To illustrate this point, tap a pencil on the table top. You hear a sound which is an audio representation of the contact dynamics between pencil tip and table top. Tactile receptors in the human fingers are known to respond up to 10 kHz [42.1]. To realistically render this type of contact between hard surfaces would require response well into the audio range of frequencies (up to 20 kHz) and thus sampling times of around 25 µs. Even with specialized designs, haptic devices do not have this bandwidth, and such high fidelity is not usually a goal of haptic rendering. Achieving stability in any type of hard contact requires very high sampling rates. In practice, most haptic simulation systems are implemented with at least 1000 Hz sampling rate. This can be reduced to the low hundreds of Hertz if the virtual environment is limited to soft materials.

Basic Haptic Rendering

The computational process of haptic rendering can be formulated into the following seven sequential steps for each cycle (Fig. 42.7). The rendering cycle must typically be completed in under 1 ms for stability and realism:

1. Sensing (Sect. 42.2.2)
2. Kinematics
3. Collision detection
4. Determining surface point
5. Force calculation
6. Kinematics
7. Actuation (Sect. 42.2.3).

Kinematics

The position and velocity measurements acquired by sensors are typically in joint space. These must be converted through the forward kinematics model and the Jacobian matrix (Chap. 2) to the Cartesian position and velocity of the operator's hand or fingertip. In some applications the operator is virtually holding a tool or object whose shape is represented in the virtual environment but whose position and orientation are determined by the operator. In whose others, the operator's fingertip or hand is represented by a point which makes only point contact with objects in the virtual environment (VE). We refer to a virtual handheld object as a virtual tool and, following [42.39], we refer to the single end-point as the haptic interaction point (HIP).

Collision Detection

For the point contact case, the collision detection software must determine if the position of the HIP at the current instant of time represents contact with a virtual object. In practice this usually means to determine if the HIP is penetrating or inside the object surface. The object surface is represented by a geometric model such as polygons or splines.

Although there is an extensive literature on collision detection in computer graphics, there are unique aspects of the collision detection problem for haptics. In particular, speed of computation is paramount and worst-case speed, as opposed to average speed, is what counts. Solutions that evaluate in constant time are pre-

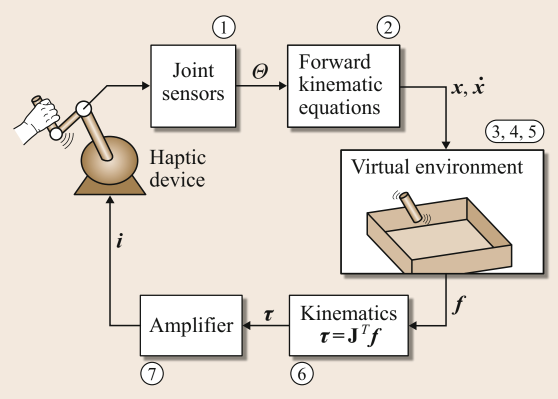

Fig. 42.7 Schematic diagram of the haptic rendering cycle for an impedance haptic display system. Virtual object moves in the virtual environment according to operator's displacement of the haptic device. Joint displacements (Θ) sensed in the device (1) are processed through kinematics (2), collision detection (3), surface point determination (4), force calculation (5), kinematics (6), and actuation (7)

ferred. Section 42.3.1 addresses collision detection and haptic rendering for complex environments.

If the HIP is found to be outside all objects, then a force of zero is returned.

Determining Surface Point

Once it is determined that the HIP is inside a surface, the force to be displayed to the operator must be computed. Many researchers have used the idea of a virtual spring connecting the HIP to the nearest point on the surface as a model of interpenetration and force generation [42.39–41]. Basdogan and Srinivasan named this point the intermediate haptic interaction point (IHIP). However all of these authors realized that the closest surface point is not always the most faithful model of contact. For example, as the HIP moves laterally below the top surface of a cube (Fig. 42.8), eventually it becomes close enough to the edge that the closest surface point becomes the side of the cube. In this situation, the algorithm needs *memory* to keep the IHIP on the top surface and generate an upward force at all times or the operator is suddenly ejected out the side of the cube.

Force Calculation

Force is commonly computed by using the spring model (Hooke's Law)

$$\boldsymbol{f} = k\boldsymbol{x} \,, \tag{42.3}$$

where $\boldsymbol{x}$ is the vector from the HIP to the IHIP, and $k > 0$. When k is sufficiently large, the object surface will feel like a wall perpendicular to $\boldsymbol{x}$. This *virtual wall*, or impedance surface, is a fundamental building block

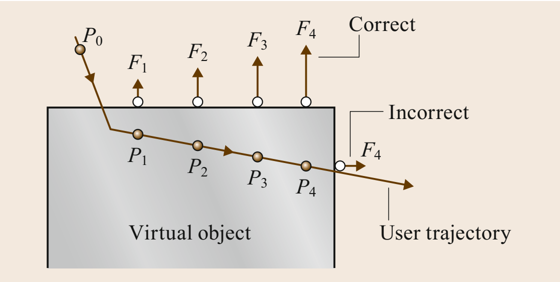

Fig. 42.8 Illustration of subtle aspects of haptic rendering of contact force. The operator fingertip trajectory enters object surface moving down and to right. Haptic interaction points (HIP) are shown at times 1–4 (*solid circles*, P_0–P_4). Intermediate haptic interaction points (IHIP) are shown when the HIP is inside the object (*open circles*). At position P_4, the algorithm must not render force based on the closest surface point or the operator will be ejected from the side of the object (feeling unnatural force tangential to the top surface)

of most haptic virtual environments. Because the virtual wall is only displayed if a collision between the HIP and virtual object is detected, the wall is a unilateral constraint, governed by a nonlinear switching condition. As will be described in the following section, haptic virtual environments with complex geometries are often formed using a polygonal mesh in which each polygon is essentially a virtual wall. A virtual surface may also be allowed to deform globally, while the local interaction with the operator is governed by a virtual wall. *Virtual fixtures*, which are often constructed from virtual walls, can be overlaid on haptic feedback teleoperators to assist the operator during a teleoperated task (Chap. 43).

The pure stiffness model described above can be augmented to provide other effects, particularly through the use of the *virtual coupling* described in Sect. 42.3.2. Damping can be added perpendicular or parallel to the surface. In addition, Coulomb or other nonlinear friction may be displayed parallel to the surface. To provide a more realistic display of hard surfaces, vibrations can also be displayed open loop at the moment of collision between the HIP and the surface, as is described in Sect. 42.5.

Kinematics

The computed force in Cartesian space must then be transformed into torques in the actuator space. Typically the calculation is

$$\boldsymbol{\tau} = \mathbf{J}^{\mathrm{T}}\boldsymbol{f} \,, \tag{42.4}$$

where $\boldsymbol{\tau}$ is the torque command to the actuators, $\boldsymbol{f}$ is the desired force vector, and $\mathbf{J}^{\mathrm{T}}$ is the transpose of the haptic device Jacobian matrix (Chap. 2). If the haptic device has no dynamics and the actuators are perfect, the exact desired force is displayed to the operator. However, real device dynamics, time delays, and other nonidealities result in applied operator forces that differ from the desired forces.

42.3.1 Rendering Complex Environments

Today's computer power is sufficient that a variety of relatively simple algorithms can effectively render haptics for simple virtual environments, say consisting of a handful of simple geometric primitives such as spheres, cubes, and planes. However, the challenge is to scale these algorithms to complex environments such as those we are used to seeing in computer graphic renderings consisting of 10^5–10^7 polygons. A variety of approaches have been tried in the literature for efficient rendering of complex scenes. *Zilles* and *Salisbury* [42.40] found planar constraints due to the nearby surface polygons and solved for the closest IHIP point using Lagrange multipliers. *Ruspini* and *Khatib* [42.42] added force shading and friction models. *Ho* et al. [42.39] used a hierarchy of bounding spheres to determine the initial contact (collision) point, but thereafter searched neighboring surfaces, edges, and vertices (referred to as geometric primitives) of the current contacted triangle to find the closest point for the IHIP. *Gregory* et al. [42.43] imposed a discretization of three-dimensional (3-D) space onto the hierarchy to speed up the detection of initial contact with the surface. *Johnson* et al. [42.44] performed haptic rendering on moving models based on local extrema in distance between the model controlled by the haptic device and the rest of the scene. *Lin* and *Otaduy* [42.45, 46] used level-of-detail representations of the objects for performing multiresolution collision detection, with the goal of satisfying real-time constraints while maximizing the accuracy of the computed proximity information.

Alternative algorithms and efficiencies can be derived by not representing the object surface as polygons. *Thompson* and *Cohen* [42.47] derived the mathematics for computing the interpenetration depth for surfaces directly from non-uniform rational B-spline (NURBS) models. *McNeely* et al. [42.18] took the extreme approach of voxelizing space at the millimeter scale. Each voxel contained a precomputed normal vector, stiffness properties, etc. 1000 Hz rendering was achieved with very complex CAD models containing millions of polygons (in the graphical equivalent representation), but large amounts of memory and precomputation are required. The performance of this algorithm is sufficiently high that it can be used to render hundreds of contact points simultaneously. This allows the operator to hold an arbitrarily shaped tool or object. The tool/object is populated by points surrounding its surface and the resultant force and moment on the tool is the sum of interaction forces computed on all of the surface points.

For surgical simulation, researchers have focused on the modeling and haptic rendering of the interaction between surgical instruments and organs. Researchers have attempted to model virtual tissue behavior in a wide variety of ways, which can be broadly classified as:

1. Linear elasticity based
2. Nonlinear (hyperelastic) elasticity-based finite-element (FE) methods
3. Other techniques that are not based on FE methods or continuum mechanics.

While most conventional linear and nonlinear FE algorithms cannot be run in real time, methods such as preprocessing can allow them to run at haptic rates [42.48]. Many researchers rely on data acquired from real tissues to model organ deformation and fracture accurately. Major challenges in this field include the modeling of connective tissue supporting the organ, friction between instruments and tissues, and topological changes occurring during invasive surgical procedures.

42.3.2 Virtual Coupling

So far we have rendered forces by computing the length and direction of a virtual spring and applying Hooke's Law (42.3). This spring is a special case of a *virtual coupling* [42.41] between the HIP and the IHIP. The virtual coupling is an abstraction of the interpenetration model of force rendering. Instead of viewing the objects as compliant, we assume them to be rigid but connect them to the operator through a virtual spring. This imposes an effective maximum stiffness (that of the virtual coupling).

Problems with stable contact rendering (Sect. 42.4) often require more sophisticated virtual couplings than a simple spring. For example, damping can be added, generalizing the force rendering model of (42.3) to

$$\boldsymbol{f} = k\boldsymbol{x} + b\dot{\boldsymbol{x}} \,. \tag{42.5}$$

The parameters k and b can be empirically tuned for stable and high-performance operation. More-formal design methods for the virtual coupling are covered in Sect. 42.4.

42.4 Control and Stability of Force Feedback Interfaces

Introduction to the Problem

The haptic rendering system depicted in Fig. 42.7 is a closed-loop dynamical system. It is a challenge to render realistic contact forces yet retain the stable behavior of human-environment contact in the natural world. Instability in haptic interfaces manifests itself as buzzing, bouncing, or even wildly divergent behavior. The worst case for impedance devices is during attempted contact with stiff objects. Empirically, instability is frequently encountered when developing haptic interfaces with stiff virtual objects, but this instability can be eliminated by reducing the stiffness of the virtual object or by the operator making a firmer grasp on the haptic device.

Problem Description in Classical Control Terms

Although linear theory is of very limited use in haptic control applications, it can be applied to a basic analysis of the factors affecting instability [42.49]. Such a highly simplified model of an impedance device is shown in Fig. 42.9. $G_1(s)$ and $G_2(s)$ represent dynamics of the haptic device for both operator position sensing and force display respectively. Assume that the virtual environment and human operator/user (HO) can each be represented by a linear impedance such as

$$Z_{\mathrm{VE}} = \frac{F_{\mathrm{VE}}(s)}{X_{\mathrm{VE}}(s)} , \quad (42.6)$$

$$Z_{\mathrm{HO}} = \frac{F_{\mathrm{HO}}(s)}{X_{\mathrm{HO}}(s)} . \quad (42.7)$$

Then the loop gain of the closed-loop system from the human operator and back again is

$$G_l(s) = G_1(s)G_2(s)\frac{Z_{\mathrm{VE}}(s)}{Z_{\mathrm{HO}}(s)} . \quad (42.8)$$

Stability in the classical sense is assessed by applying the magnitude and phase criteria of Nyquist to $G_l(s)$. Increasing Z_{VE} (corresponding to stiffer or heavier virtual objects) increases the magnitude of $G_l(s)$ and thus destabilizes the system while a firmer grasp by the human operator, which increases the magnitude of Z_{HO}, has a stabilizing effect. Similar arguments apply to phase shifts that might be present in any part of the system.

Limitations of Linear Theory

Although the model of Fig. 42.9 illustrates some qualitative features of haptic interface stability, linear continuous time theory is of little use in designing methods to stabilize the loop. Interesting virtual environments are nonlinear. Furthermore, they can rarely be linearized because applications often simulate discontinuous contact, for example, between a stylus in free space and a hard surface. A second feature is digital implementation, which introduces sampling and quantization – both of which have significant effects.

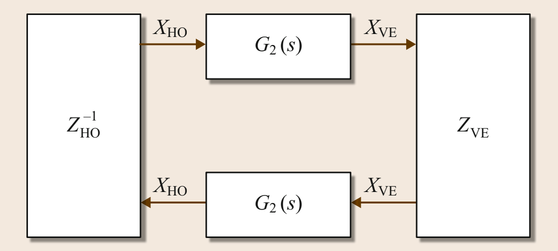

Fig. 42.9 Highly simplified linear model of haptic rendering to highlight some stability issues

Sampling

Colgate et al. [42.41] incorporated consideration of discrete time sampling behavior in the stability analysis. They considered the problem of implementing a virtual wall of stiffness

$$H(z) = K + B\frac{z-1}{Tz} , \quad (42.9)$$

where K is the virtual wall stiffness, B is the virtual wall damping coefficient, z is the z-transform variable, and T is the sampling time. They further modeled the haptic device (HD) in continuous time as

$$Z_{\mathrm{HD}}(s) = \frac{1}{ms+b} , \quad (42.10)$$

where m and b are the mass and damping of the haptic device, respectively. They derived the following condition for passivity of the device

$$b > \frac{KT}{2} + |B| , \quad (42.11)$$

showing a significant stabilizing effect of high sampling rates and also of high mechanical damping in the haptic device.

Quantization

Additional factors include delays due to numerical integration schemes and quantization. These contributing factors to instability have been termed *energy leaks* by *Gillespie* and *Cutkosky* [42.50].

Passivity

Interesting virtual environments are always nonlinear and the dynamic properties of a human operator are important. These factors make it difficult to analyze haptic systems in terms of known parameters and linear control theory. One fruitful approach is to use the idea of passivity to guarantee stable operation. Passivity is a sufficient condition for stability, and is reviewed more completely in Chap. 43 on telerobotics. There are many similarities between the control of haptic interfaces and bilateral teleoperation.

The major problem with using passivity for design of haptic interaction systems is that it is overly conservative, as shown in [42.35]. In many cases, performance can be poor if a fixed damping value is used to guarantee passivity under all operating conditions. *Adams* and *Hannaford* derived a method of virtual coupling design from two-port network theory which applied to all causality combinations and was less conservative than passivity based design [42.51]. They were able to derive optimal virtual coupling parameters using a dynamic model of the haptic device and by satisfying Lewellyn's *absolute stability criterion*, an inequality composed of terms in the two-port description of the combined haptic interface and virtual coupling system. *Miller* et al. derived another design procedure which extended the analysis to nonlinear environments and extracted a damping parameter to guarantee stable operation [42.52–54].

42.5 Other Types of Haptic Interfaces

While kinesthetic (force feedback) haptic interfaces have the closest relationship to robotics, there are a variety of other types of haptic interfaces which are usually classified as tactile displays. Tactile displays are used to convey force, contact and shape information to the skin. They purposely stimulate cutaneous receptors, with little effect on kinesthetic sensation. This is in contrast to kinesthetic displays, which must inherently provide some cutaneous sensations through physical contact with a tool or thimble, but whose primary output is force or displacement to the limbs and joints. Tactile displays are usually developed for a specific purpose, such as display of contact events, contact location, slip/shear, texture, and local shape. Special purpose tactile displays can be targeted at different types of cutaneous receptors, each with its own frequency response, receptive field, spatial distribution, and sensed parameter (e.g., local skin curvature, skin stretch, and vibration) and each receptor type is associated with different exploratory procedures described in Sect. 42.1.1.

In contrast, tactile displays that render contact information for virtual reality or teleoperation have proven far more challenging. Accurate recreation of the local shape and pressure distribution at each fingertip requires a dense array of actuators. Devices specifically aimed at tactile perception are an active area of research but most have not reached the stage of applications or commercial distribution, with the notable exception of Braille displays for the blind. In this section, we describe the various types of tactile displays, their design considerations and specialized rendering algorithms, and applications.

42.5.1 Vibrotactile Feedback

Vibrotactile feedback is a popular method of providing tactile feedback. It can be used as a stand-alone method for haptic feedback or as an addition to a kinesthetic display. Vibrating elements, such as piezoelectric materials and small voice-coil motors, are lighter than the actuators used in kinesthetic devices, and can often be added to kinesthetic devices with little impact on existing mechanisms. In addition, high-bandwidth kinesthetic displays can be programmed to display open-loop vibrations through their normal actuators. The sensitivity for human vibration sensing ranges from DC to over 1 kHz, with peak sensitivity around 250 Hz.

We first consider the use of vibrations to convey impact or contact events – a technique that straddles kinesthetic and tactile feedback. When humans touch an environment, fast-acting sensors embedded in the skin record the minute vibrations occurring from this interaction. As described in Sect. 42.3, conventional approaches to haptic display usually consist of designing a virtual model with simple geometry, then using a first-order stiffness control law to emulate a surface. However, such first-order models often lack the realism of higher-order effects such as impact. With common haptic rendering algorithms, surfaces feel squishy or unrealistically smooth. One solution to improving the realism of such environments is to add higher-order effects such as textures and contact vibrations. These effects can use a library of surface models based on ad hoc analytical descriptions [42.55], which are sometimes tuned using qualitative operator feedback, physical measurements (reality-based models created from empirical data) [42.56, 57], or a combination of the two [42.58]. At the instant collision is detected between the HIP and a surface of the virtual object, the appropriate waveform is called out of the library, scaled according to the context of the motion (such as velocity or acceleration), and played open loop through an actuator. That actuator may be the same one simultaneously displaying lower-frequency force information, as shown in Fig. 42.10, or it might be a separate transducer. *Kuchenbecker* et al. [42.59] considered the dynamics of the haptic device to display the most accurate vibration waveforms possible, and compared a number of different vibration waveform generation techniques meant to convey impact superimposed on force feedback in virtual environments. Most of the vibration feedback methods performed similarly in terms of realism, and they were also significantly more realistic than conventional force feedback alone.

Vibration feedback can also be used to provide information about patterned textures, roughness, and other phenomena that have clear vibratory signals. This type of vibration feedback is often termed *vibrotactile* feedback. In teleoperated environments, *Kontarinis* and *Howe* [42.60] showed that damaged ball bearings could be identified through vibration feedback, and *Dennerlein* et al. [42.61] demonstrated that vibration feedback improved performance over no haptic feedback, for a telemanipulation task inspired by undersea field robotics. In these teleoperator systems, vibration-sensitive sensors such as accelerometers and piezoelectric sensors are used to pick up and, in most cases, directly provide the vibration signals as inputs to a vibrotactile actuator. In virtual environments, *Okamura* et al. [42.62] displayed vibrations modeled based on textures and puncture of a membrane. Similar to the event-based haptics above, the vibration waveforms were modeled based on earlier experiments and played open loop during interaction with the virtual environment.

Finally, vibration feedback has been used as a method of sensory substitution, to convey direction, attention, or other information, e.g., [42.63–65]. In this case, the strength and clarity of the signal, not realism, is the goal. Vibration frequencies near the peak human sensitivity are most effective, and there exist commercially available vibrotactile actuators (or *tactors*) suitable for such applications, e.g., Engineering Acoustic, Inc.'s C2 Tactor [42.66]. Elements within an array of tactors can be selectively turned on and off to evoke the sensory saltation phenomenon, in which a pattern of brief pulses on a series of tactors is perceived not as successive taps at different locations, but as a single tap that is traveling or hopping over the skin.

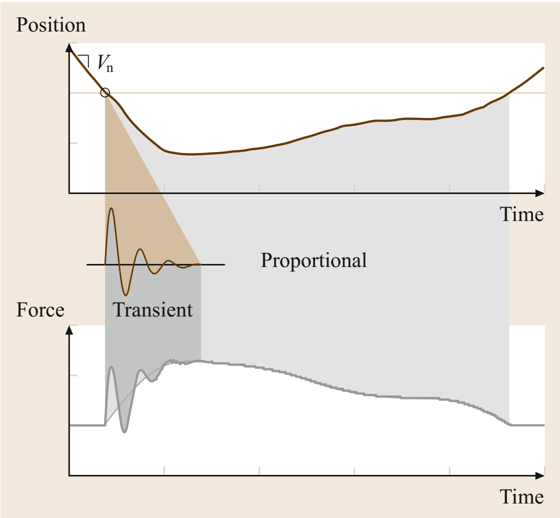

Fig. 42.10 Event-triggered open-loop force signals superimpose on traditional penetration-based feedback forces, providing vibration feedback that improves the realism of hard surfaces in virtual environments (after [42.59] with permission)

42.5.2 Contact Location, Slip, and Shear Display

In early work related to robotic dexterous manipulation, it was found that knowledge of the contact point between a robot hand and a grasped object is essential for manipulation. Without this knowledge, the robot will easily drop the object due to rapid accumulation of grasp errors. While many robotics researchers and some companies have developed tactile array sensors capable of measuring contact location, pressure distribution, and local object geometry (Chap. 28), practical methods for display of this information to the human operator of a virtual or teleoperated environment have proven much more difficult. We begin our discussion of contact display by considering contact location, slip, and shear display, which have the common goal of displaying the motion of a single area of contact relative to the skin (almost invariably on a finger). Arrays of pins that rise and fall to create a pressure distribution on the skin have been the most popular method to date for displaying contact information, but we will address those designs in the following section on local shape, since their primary advantage is the display of spatially distributed information. Instead, we will focus here on tactile devices that are designed to specifically address the problem of contact location and motion.

As an example of contact location display, *Provancher* et al. [42.67] developed a system that renders the location of the contact centroid moving on the user's fingertip. The tactile element is a free-rolling cylinder that is normally suspended away from the fingertip, but comes into contact with the skin when the operator pushes on a virtual object. The motion of the cylinder over the skin is controlled by sheathed push-pull wires. This allows the actuators to be placed remotely, creating a lightweight, thimble-sized package that can be unobtrusively mounted on a kinesthetic haptic device. An experiment demonstrated that human operators performed similarly during real manipulation and virtual manipulation (using the tactile display) in an object curvature discrimination task. In addition, operators were able to use the device to distinguish between manipulations of rolling and anchored but rotating virtual objects.

42.5.3 Slip and Shear

Humans use slip and incipient slip widely during manipulation tasks [42.68]. To reproduce these sensations for experiments to characterize human slip sensation, researchers have created stand-alone 1-DOF slip displays [42.69–71]. *Webster* et al. [42.71] created a 2-DOF tactile slip display, which uses an actuated rotating ball positioned under the user's fingertip. The lightweight, modular tactile display can be attached to a multi-DOF kinesthetic interface and used to display virtual environments with slip. Experimental results demonstrate that operators complete a virtual manipulation task with lower applied forces using combined slip and force feedback in comparison with conventional force feedback alone. Skin stretch can also be integrated with a slip display to provide information about pre-slip conditions. For example, *Tsagarakis* et al. [42.72] developed a lightweight device that uses a V configuration of miniature motors to provide sensations of relative lateral motion (direction and velocity) onto the operator's fingertips. Generation of two-dimensional (2-D) slip/stretch is achieved by coordinating the rotational speed and direction of the two motors.

In terms of tactile device kinematics, slip and shear displays can be quite similar. However, the goal of shear, or skin stretch, displays is to maintain a no-slip condition such that shear forces/motions can be accurately controlled with respect to the human operator, typically on the finger. The use of shear (tangential skin stretch) is motivated by perceptual experiments demonstrating that the human fingerpad is more sensitive to tangential displacement compared to normal displacement [42.73]. A variety of tangential skin stretch devices have been designed, with applications in wearable haptics, high-fidelity tactile rendering, and teleoperation. *Hayward* and *Cruz-Hernandez* [42.74] developed a tactile device consisting of closely packed piezoelectric actuators, which generates a programmable stress field within the fingerpad. Single skin-stretch *tactors* have also been used to convey two-dimensional directional information (for navigation) [42.75] and to enhance perception of virtual environments (e.g., friction) [42.76] alone or in combination with kinesthetic haptic interfaces. A similar approach has been used for 3-DOF skin stretch, in combination with cutaneous normal force [42.77, 78]. In a different form factor, researchers have developed rotational skin stretch devices that can act as a substitute for natural proprioceptive feedback [42.79, 80].

42.5.4 Local Shape

Most tactile devices for local shape display consist of an array of individual pin elements that move normal to the surface. Often, a layer of elastic material is used to cover the pins so that the operator contacts a smooth surface rather than the pins directly. Other systems use individual elements that move laterally, and some substitute electrodes for moving parts to form an array of electrocutaneous elements. A number of researchers have used psychophysical and perceptual experimental results to define design parameters such as number of pins, spacing, and amplitude of pin-based tactile displays. A commonly used metric is the two-point discrimination test, which defines the minimum distance between two contact points on the skin at which they are perceived as two, rather than one point. This discrimination limit varies widely for skin on different parts of the body, with the fingertips having one of the smallest (usually cited as less than 1 mm, although this depends on the shape and size of the contacts) [42.81, 82]. *Moy* et al. [42.83] quantified several perceptual capabilities of the human tactile system based on predicted subsurface strain and psychophysical experiments that measured amplitude resolution, the effects of shear stress, and the effects of viscoelasticity (creep and relaxation) on tactile perception for static touch. They found find that 10% amplitude resolution is sufficient for a teletaction system with a 2 mm elastic layer and 2 mm tactor spacing. A different type of experiment examines the kind of tactile information relevant to a particular application. For example, *Peine* and *Howe* [42.84] found that sensed deformation of the fingerpad, and not changes in pressure distribution, were responsible for localizing lumps in a soft material, such as a tumor in tissue.

We will now highlight a few distinctive designs of array-type tactile displays. A number of actuator technologies have been applied to create tactile arrays, including piezoelectric, shape-memory alloy (SMA), electromagnetic, pneumatic, electrorheological, microelectromechanical system (MEMS), and electrotactile. Further reading on tactile display design and actuation is available in review papers, including [42.85–90].

We will first consider two ends of the spectrum in complexity/cost of the pin-based approach. *Killebrew* et al. [42.91] developed a 400-pin, 1 cm^2 tactile stimulator to present arbitrary spatiotemporal stimuli to the skin for neuroscience experiments. Each pin is under independent computer control and can present over 1200 stimuli per minute. While not practical for most haptic applications due to the size and weight of the actuation unit, it is the highest-resolution tactile display built to date and can be used to evaluate potential designs for lower-resolution displays. *Wagner* et al. [42.92] created a 36-pin, 1 cm^2 tactile shape display that uses commercially available radio-controlled (RC) servomotors. The display can represent maximum frequencies of 7.5–25 Hz, pending on the amount of pin deflection, and is shown in Fig. 42.11. *Howe* et al. [42.93, 94] have also explored the use of shape-memory alloys for pin actuation, for the application of remote palpation.

In contrast to pins that move normal to the surface, recent tactile array designs have incorporated pins that move laterally. First introduced by *Hayward* and *Cruz-Hernandez* [42.95], the most recent compact, lightweight, modular design [42.96] uses a 6×10 piezo bimorph actuator array with a spatial resolution of $1.8\,mm \times 1.2\,mm$. The force of the individual actuators provides sufficient skin pad motion/stretch to excite mechanoreceptors [42.97]. A pilot test demonstrated that subjects could detect a virtual line randomly located on an otherwise smooth virtual surface, and the device has also been tested as a Braille display [42.98]. Another lateral stretch display and its evaluation is described in [42.99]. Other novel approaches to tactile display include sending small currents through the skin or tongue using an electrocutaneous array [42.100] and the application of air pressure to stimulate only superficial mechanoreceptors [42.101].

42.5.5 Surface Displays

In recent years, the concept of surface displays, which modulate surface friction in order to display changing shear forces as a user moves the finger over the surface. One example device that uses slip and friction to display compelling tactile sensations is the TPaD

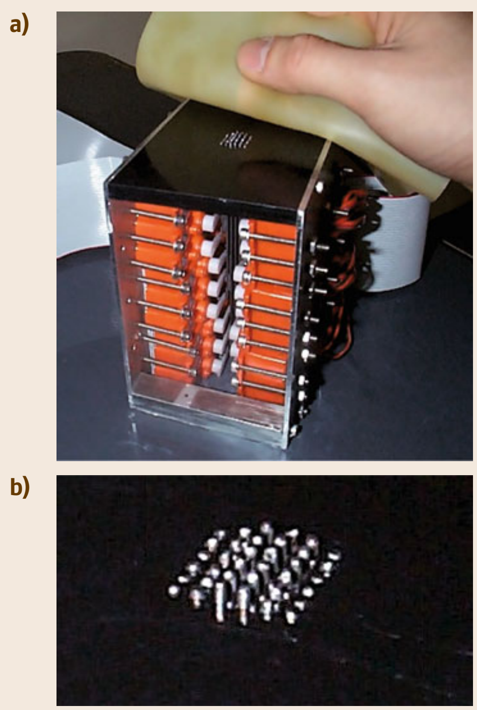

Fig. 42.11 **(a)** A low-cost 36-pin tactile display using RC servomotor actuation. **(b)** A closeup of the 6×6 display, showing a sine wave grating (after [42.92] with permission)

(tactile pattern display) [42.102]. Ultrasonic frequency, low amplitude vibrations of a flat plate create a film of air between the plate and a human finger touching the plate, thereby reducing friction. The 33 kHz vibration of the plate cannot be perceived by the human. The amount of friction reduction varies with vibration amplitude, allowing indirect control of shear forces on the finger during active exploration. Finger position and velocity feedback enables haptic rendering of spatial texture sensations. This work has been expanded into a variety of different surface displays, including devices that generate active forces [42.103] and those that use electrostatic forces to modulate friction [42.104, 105].

42.5.6 Temperature

Because the human body is typically warmer than objects in the environment, thermal perceptions are based on a combination of thermal conductivity, thermal capacity, and temperature. This allows us to infer not only temperature difference, but also material composition [42.106]. Most thermal display devices are based on thermoelectric coolers, also known as Peltier heat pumps. Thermoelectric coolers consist of a series of semiconductor junctions connected electrically in series and thermally in parallel. The thermoelectric cooler is designed to pump heat from one ceramic faceplate to the other, but if used in reverse, a temperature gradient across the device produces a proportional potential; as a measure of relative temperature change. The designs of haptic thermal displays mostly use off-the-shelf components, and their applications are typically straightforward, enabling identification of objects in a virtual or teleoperated environment by their temperature and thermal conductivity.

Ho and *Jones* [42.107] provide a review of haptic temperature display, as well as promising results suggesting that a thermal display is capable of facilitating object recognition when visual cues are limited. Although numerous systems have integrated thermal display with other types of haptic display, the Data Glove Input System designed by *Caldwell* et al. [42.108, 109] was one of the first to do so. Their haptic interface provides simultaneous force, tactile, and thermal feedback. The Peltier device used for thermal display contacts the dorsal surface of the index finger. Subjects achieved a 90% success rate in identifying materials such as a cube of ice, a soldering iron, insulating foam, and a block of aluminum, based only on thermal cues. The study of human temperature perception is particularly interesting, including issues such as spatial summation and the psychological relevance of temperature display. For example, in prosthetic limbs, temperature display may be useful not only for practical reasons such as safety and material identification, but also for reasons of personal comfort, such as feeling the warmth of a loved one's hand.

42.6 Conclusions and Further Reading

Haptic technology, which attempts to provide compelling sensations to human operators in virtual and teleoperated environments, is a relatively new, but fast-growing and dynamic area of research. The field relies not only on fundamental foundations from robotics and control theory, but also on fields in the human sciences, particularly neuroscience and psychology. To date, commercial success of haptics has been in the areas of entertainment, medical simulation, and design, although novel devices and applications are regularly appearing.

There exist many books on the topic of haptic technology, most of them compendiums from workshops or conferences on the subject. One of the earliest books on haptics, by *Burdea* [42.110], provides a thorough review of applications and haptic devices up to 1996. A book specifically focused on haptic rendering, designed for potential use as a textbook, has been edited by *Lin* and *Otaduy* [42.111]. In addition, we recommend the following useful articles: *Hayward* and *MacLean* [42.112, 113] describe the fundamentals of constructing experimental haptic devices of modest complexity, the software components needed to drive them, and the interaction design concepts important to creating usable systems. *Hayward* et al. [42.114] also provide a tutorial on haptic devices and interfaces. *Salisbury* et al. [42.115] describe the basic principles of haptic rendering. *Hayward* and *MacLean* [42.116] describes a number of tactile illusions that can inspire creative solutions for haptic interface design. *Robles-De-La-Torre* [42.117] underscores the importance of haptics with compelling examples of humans who have lost the sense of touch.

Finally, there exist two journals that are specific to the field of haptics: *Haptics-e* [42.118] and *IEEE Transactions on Haptics* (first issue expected 2008). Several conferences are specifically devoted to haptics: Eurohaptics and the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems are held separately in even years, and on the odd years become a single conference, World Haptics. The IEEE (Institute of Electrical and Electronics Engineers) technical committee on haptics [42.119] provides information about relevant publication forums.

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