Chapter 2
Introduction to Haptics

2.1 Definition of Haptics

The word *haptic* originates from the Greek verb *hapto—to touch*—and therefore refers to the ability to touch and manipulate objects. The haptic experience is based on tactile senses, which provide awareness of the stimuli on the surface of the body and kinesthetic senses, which provide information about body pose and movement. Its bidirectional nature is the most prominent feature of haptic interaction, which enables exchange of (mechanical) energy—and therefore information—between the body and the outside world.

The word *display* usually emphasizes the unidirectional nature of transfer of information. Nevertheless, in relation to haptic interaction, similar to visual and audio displays, the phrase *haptic display* refers to a mechanical device for transfer of kinesthetic or tactile stimuli to the user.

The term haptics often refers to sensing and manipulation of virtual objects in a computer-generated environment—a synthetic environment that interacts with a human when performing sensory-motor tasks. A typical virtual reality system consists of a head-mounted display, which projects computer-generated images and sound based on the user's head orientation and gaze direction and a haptic device that allows interaction with a computer through gestures. Synthesis of virtual objects requires an optimal balance between the user's ability to detect object's haptic properties, the computational complexity required to render objects in real time and the accuracy of haptic devices for generating mechanical stimuli.

Virtual environments that engage only the user's visual and auditory senses are limited in their ability to interact with the user. It is desirable to also include a haptic system that not only transmits sensations of contact and properties of objects, but also allows their manipulation. The human arm and hand enable pushing, grasping, squeezing, or hitting the objects, they enable exploration of object properties such as surface texture, shape and compliance and they enable manipulation of tools such as a pen or a hammer. The ability to touch, feel and manipulate objects in a virtual environment, augmented with visual and auditory perception, enables a degree of

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immersion that otherwise would not have been possible. The inability to touch and feel objects, either in a real or a virtual environment, impoverishes and significantly affects the human ability of interaction with the environment [1].

A haptic interface is a device that enables interaction with virtual or physically remote environments [2, 3]. It is used for tasks that are usually performed by hand in the real world, such as manipulating objects and exploring their properties. In general, a haptic interface receives motor commands from the user and displays the appropriate haptic image back to the user. Haptic interactions may be augmented with other forms of stimuli such as stimulation of visual or auditory senses.

Although haptic devices are typically designed for interaction with the hand, there are a number of alternative options that are appropriate for sensory and motor properties of other parts of the body. In general, a haptic interface is a device that: (1) measures position or contact force (and/or their time derivatives and spatial distribution) and (2) displays contact force or position (and/or their spatial and time distribution) to the user.

Figure 2.1 shows a block diagram of a typical haptic system. A human operator is included in the haptic loop through a haptic interface. The operator interacts with a haptic interface either through force or movement. The interface measures human activity. The measured value serves as a reference input either to a teleoperation system or a virtual environment. A teleoperation system is a system in which a usually remote slave robot accomplishes tasks in the real environment that the human operator specifies using the haptic interface. Interaction with a virtual environment is similar, except that both the slave system and the objects manipulated by it are part of the programmed virtual environment. Irrespective of whether the environment is real or virtual, control of the slave device is based on a closed loop system that compares the output of the haptic interface to the measured performance of the slave system. The essence of haptic interaction is the display of forces or movements, which are the result of the operation of the slave system, back to the user through the haptic interface. Therefore, it is necessary to measure forces and movements that occur in teleoperation or compute forces and movements that are the result of interaction with a virtual environment. Since force may be a result of movement dynamics or interactions of an object with other objects or with the slave system, collision detection represents a significant part of the haptic loop. As already mentioned, contact can occur either between objects in the environment (real or virtual) or between an object and the slave system. Collision detection in a real environment is relatively straightforward and is essentially not much more than the measurement of interaction forces between the robot and its surroundings. In contrast, collision detection in a virtual environment is a more complex task since it requires computation of contact between virtual objects that can be modeled using different methods. In this case, it is necessary to compute multiple contacts between outside surfaces of objects.

Collision detection forms the basis for computation of reaction forces. In a teleoperation system, force is measured directly using a force/torque sensor mounted on the slave robot end-effector. In a virtual environment, on the other hand, it is necessary to compute the contact force based on a physical model of the object. The object stiffness can, for example, be modeled as a spring-damper system, while friction can

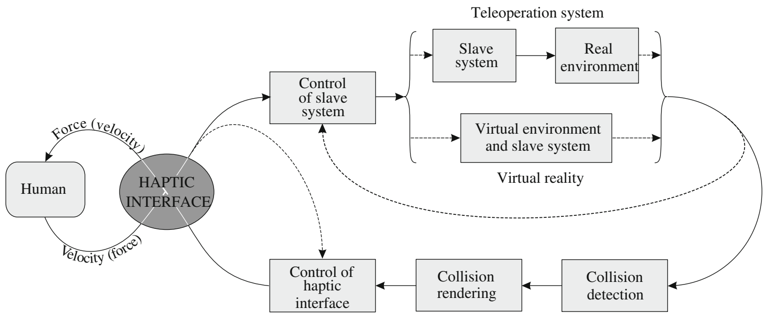

Fig. 2.1 Haptic system: interaction between a human and the haptic interface represents a bidirectional exchange of information—a human operator controls the movement of a slave system as well as receives information about the forces and movements of the slave system through the haptic interface

be modeled as a force that is tangential to the surface of the object and proportional to the normal force to the surface of the object. The computed or measured force or displacement is then transmitted to the user through the haptic interface. A local feedback loop controls the movement of the haptic interface, so that it corresponds to the measured or computed value.

From the block scheme in Fig. 2.1, it is clear that the interaction between a human and the haptic interface represents a bidirectional exchange of information—a human operator controls the movement of a slave system as well as receives information about the forces and movements of the slave system through the haptic interface. The product of force and displacement represents mechanical work accomplished during the haptic interaction. Bidirectional transfer of information is the most characteristic feature of haptic interfaces compared to display of audio and visual images.

2.2 Haptic Applications

The need for an active haptic interface depends on task requirements. *Active haptic interfaces are a must for certain tasks*. A lot of assembly and medical problems are haptic by their nature. Haptic devices are required for simulating such tasks for training purposes, since perception of force, which is the result of the interaction of a tool with the environment, is critical for successful task completion. In addition, haptic devices allow persons with vision impairments to interact with virtual environments.

Haptic devices can improve user immersion. Simple haptic devices with fewer active degrees of freedom are produced in large quantities for entertainment purposes (playing video games). Although the complexity of stimuli that may be transmitted to the user is limited, perception of the virtual environment is still relatively precise.

Haptic devices can improve the efficiency of task execution by providing natural constraints (virtual fixtures). In virtual environments, transfer of virtual objects without haptic perceptions is often difficult. Without feedback information about contact forces, simulation of an assembly task requires a great deal of attention due to reliance on visual feedback only. Haptic devices represent a suitable solution since they reduce the need for visual attention. Force feedback substantially contributes to accuracy of estimation of spatial information.

Haptic devices may reduce complexity of information exchange. In contrast to display of visual and audio images, haptic devices do not clutter the environment with unnecessary information. Haptic devices are connected to a single person. A haptic interface provides only the necessary information to the right person at the right time.

A haptic interface forms an integral part of a teleoperation system, where the haptic display is used as a master device. The haptic interface conveys command information from the operator to the slave device and provides feedback information about the interaction between the slave manipulator and the environment back to the operator.

2.3 Terminology

The terminology is defined as in [4].

A haptic display is a mechanical device designed for transfer of kinesthetic or tactile stimuli to the user. Haptic displays differ in their kinematic structure, workspace and output force. In general, they can be divided into devices that *measure movement and display force* and devices that *measure force and display movement*. The former are called *impedance displays*, while the latter are called *admittance displays*. Impedance displays typically have small inertia and are backdrivable. Admittance displays typically have much higher inertia, are not backdrivable and are equipped with a force and torque sensor.

A haptic interface comprises everything between the human and the virtual environment. A haptic interface always includes a haptic display, control software and power electronics. It may also include a virtual coupling that connects the haptic display to the virtual environment. The haptic interface enables exchange of energy between the user and the virtual environment and it is, therefore, important in the analysis of stability as well as efficiency.

A virtual environment is a computer generated model of a real environment. A virtual environment can be constructed as an exact replica of the real environment or can be a highly simplified reality. Regardless of its complexity, however, there are two completely different ways of interaction between the environment and the haptic interface. Environment may behave as impedance, where the input is the velocity or position and the output force is determined based on a physical model, or as an admittance, where the input is force and the output is velocity or position.

A haptic simulation is a synthesis of a user, haptic interface and a virtual environment. All these elements are important for stability of the system. Simulation includes continuous time elements, such as a human and a mechanical device, as well as discrete elements, such as a virtual environment and control software.

Mechanical impedance is an analogy to electrical impedance. It is defined as the ratio between force and velocity (torque and angular velocity)—an analogy of the ratio between voltage and current in electrical circuits:

$$Z(s) = \frac{F}{v} = ms + b + \frac{k}{s}, \tag{2.1}$$

where m is mass, b is a viscous damping and k is stiffness. Mechanical impedance is often defined as the ratio between force and position (displacement). This definition is related to the second-order differential equation that describes the mechanical system as

$$F = m\ddot{x} + b\dot{x} + kx. \tag{2.2}$$

In this case, impedance is defined as

$$Z(s) = \frac{F}{x} = ms^2 + bs + k. \tag{2.3}$$

Mechanical admittance represents an analogy to electrical admittance and is defined as the ratio of the velocity and force (angular velocity and torque)—an analogy of the ratio between current and voltage:

$$Y(s) = \frac{v}{F} = \frac{1}{ms + b + \frac{k}{s}}, \tag{2.4}$$

where m is the mass, b is the viscous damping and k is the stiffness. Similarly to mechanical impedance, admittance is also often defined as the ratio of position (displacement) and force

$$Y(s) = \frac{x}{F} = \frac{1}{ms^2 + bs + k}. \tag{2.5}$$

Causal structure is defined by the combination of the type of haptic display (impedance or admittance) and the virtual environment (impedance or admittance), giving a total of four possible combinations.

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