

Chapter 1

Introduction

1.1 Haptics and Haptic Display Technology

Haptic perception includes all aspects of touch using the hand. Haptic perception enables us to perform a variety of manipulation tasks with ease and accuracy and provides valuable perceptual information that other modalities sometimes can't. Simple everyday tasks such as using a key, tying a shoe, or brushing one's teeth would all become a great deal more difficult without a sense of touch. We rely on touch as we write, type, drive, and eat. The plea of a child to "let me see it", which of course actually means "let me *hold* it and *touch* it" is a testimony to the fundamental importance of touch in our experience of the world.

Yet the scientific study of touch is much less developed than that of hearing or sight. Attention from science even in this century has been limited. Revesz first introduced the term "haptics", which comes from the Greek, meaning "to touch", in 1931 (Revesz, 1950). Another notable contributor to the study of haptic perception was psychologist J. J. Gibson who, in 1966, described the haptic sense as the sensory-motor system involved in the gathering of information by hand (Gibson, 1966). Gibson and others (Heller and Schiff, 1991; Katz, 1925/1989 trans.) recognized that haptics involved multiple sensory and motor organs of the hand and arm, such as the cutaneous sensors for pressure, temperature, pain, and vibration; and sensors for position and force in the muscles and joints. These researchers also recognized the interrelation between manipulation and the

pickup of information by hand, for instance by making a distinction between *active* and *passive* touch (Gibson, 1962; Gordon , 1978; Lederman, 1981).

In recent years, interest in haptic perception has increased because of the development of man-machine systems such as telemanipulators and interactive human-computer systems (e.g. virtual reality). The desire for natural, intuitive means of human-machine interaction, and for multi-modal sensory feedback to users has resulted in the design of machines which allow users to generate control inputs using hand motion, and at the same time experience forces or resistance on their hands which create interesting and useful perceptions. These machines are called *haptic interfaces* . In the literature they are also sometimes referred to as manipulanda, hand controllers, or force-feedback joysticks. They are typically robot-like mechanisms with rigid handles which are able to move in one or more degrees of freedom. Important system components include actuators, motion and force sensors, and a digital controller.

At present, haptic interfaces are still mainly confined to research and development facilities because they are expensive and difficult to program. They are generally used in two contexts: telemanipulation and computer simulation interaction (i.e. virtual environments). A system for telemanipulation with force feedback is shown in Figure 1.1.

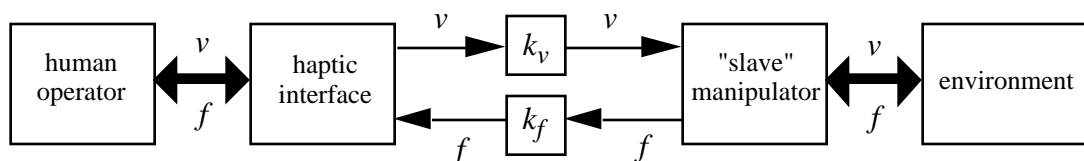


Figure 1.1 System for telemanipulation with force feedback. Mechanical connections between components are shown as a single thick line with a double arrow, indicating bilateral interaction. Signal connections are shown as two separate lines with single arrows, indicating that each signal flows in only one direction.

Telemanipulation is a scheme in which a "slave" robot arm, usually in a remote or dangerous environment, tracks the motion of a "master" manipulator (i.e. a haptic interface). The human operator physically interacts with the haptic interface, exchanging mechanical energy with it. Motion of the haptic interface is transduced and scaled by k_v . The result is sent to the slave manipulator as a motion command. The slave manipulator moves in synch with the operators motions, performing work on the environment. The forces of the interaction between the slave and the environment are in turn measured, scaled, and sent back as force commands to the haptic interface.

Certain details of a real system might be different from that shown in Figure 1.1, for example velocity and force signals might flow in the opposite direction, but the basic idea is the same: the impedance of the haptic interface is controlled to be similar to the impedance encountered by the slave manipulator. Mechanical impedance is defined as the dynamic (history-dependent) relationship between the motion input to a system, and the force output from the system, where the instantaneous product of velocity and force is the power being transferred between the interacting systems. In Figure 1.1, signal level interactions are shown as a pair of lines, each representing a signal which flows in only one direction. Power level interactions are shown as solid lines with arrows at both ends, indicating that the interaction is truly bilateral.

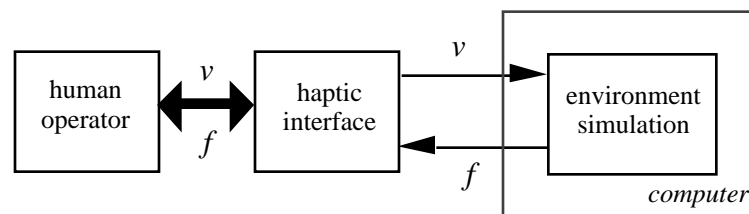


Figure 1.2 System for haptic interaction with computer simulation.

Figure 1.2 is a block diagram for a haptic interface to a computer simulated (virtual) environment. In this system, a signal representing the motion of the haptic interface is input to a computer simulation of a mechanical environment, which computes a desired reaction force. The system is similar to the telemanipulation system, except that the interaction between the slave robot and environment is simulated with a computer algorithm. Again, the input and output signals to the simulation could be reversed.

1.2 Scope of the Thesis

This thesis is a part of a research program to develop haptic interface systems, primarily for computer simulation interaction. The primary challenges to this effort are development of haptic interface *mechanisms*, and development of *software* simulations of physical systems for haptic display. A fundamental understanding of the nature of haptic interaction, including haptic perception, is essential for informing the development of these hardware and software systems. Increasing that understanding was the purpose of this thesis. The method was to conduct experiments in which human subjects used a haptic interface to perform simple tasks and detect simple features.

1.2.1 Haptic Perception and Mechanical Constraint

Haptic interfaces are unique as human-machine interfaces in that they are both input devices and display devices at the same time. They are not simply passive displays. The haptic modality is also unique in that it typically involves significant exchange of energy (in this case mechanical energy) between a user and the interface. This creates potential problems, e.g. unsafe forces, speeds, or oscillations, but it also provides opportunities for improving human performance when the energy provided by the interface is structured properly. A simple example is to create a potential well in the vicinity of a target position. The haptic interface will tend to move toward the target, bringing the user along with it.

Another example is simulating a rigid surface or "wall" which impedes motion past a certain boundary. The potential well and the wall are mechanical features of the environment that influence the trajectory of the haptic display. I refer to these features as mechanical *constraints*. Effective use of mechanical constraints in simulated environments

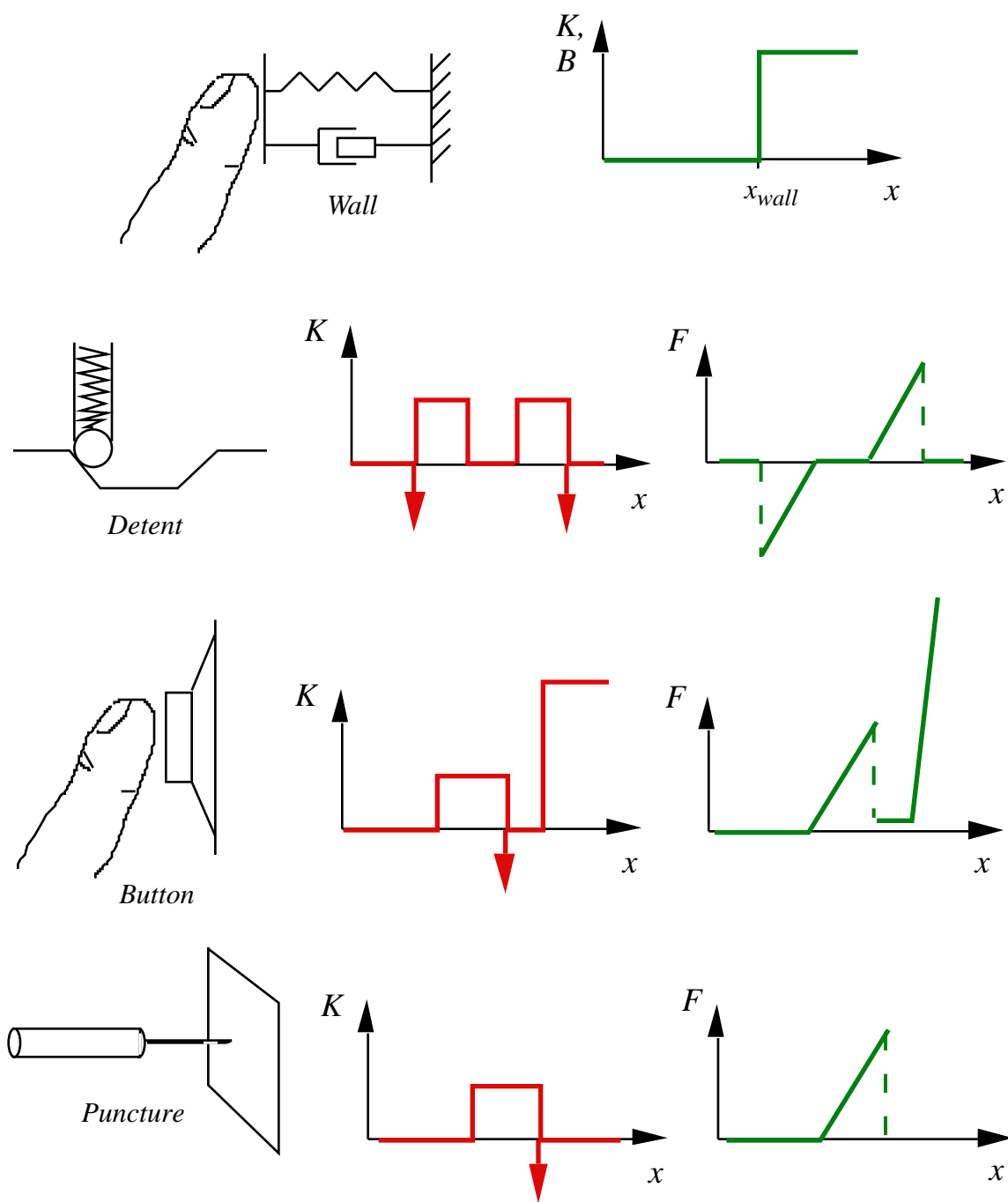


Figure 1.3(a-d) Simulations of simple environments using step-changes in damping and stiffness. Step changes in force are represented as delta functions in stiffness.

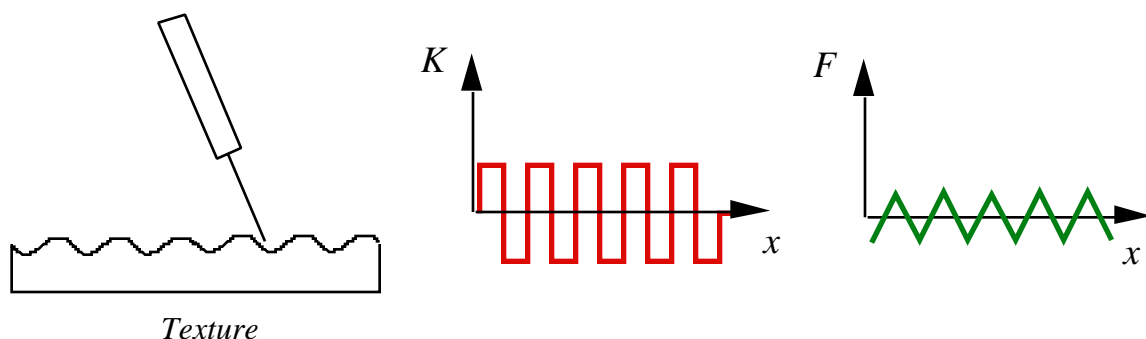


Figure 1.3(e) Model of texture as variations in stiffness.

The examples in Figure 1.3 have all been implemented by researchers in the field. Modeling hard surfaces as a linear spring and damper is nearly ubiquitous (Rosenberg & Adelstein, 1993; Massie & Salisbury, 1994; Colgate & Brown, 1994). The haptic detent shown was implemented by Adelstein (1989), and the button by Massie and Salisbury (1994). MacLean (1995) also used similar models to simulate toggle switches. The model for puncture was used by Massie (personal conversation, 1994). The same model was also used by Gillespie (1993) to simulate a harpsichord key. Minsky (1995) studied the perception of texture using variations of the model above.

It should be clear from the examples that a wide variety of static (non-inertial) mechanical systems can be simulated with piecewise linear damping and stiffness. Yet the models are relatively simple – only a few parameters are needed to describe each environment. Since position-dependent damping and stiffness are so widely used for simulating mechanical environments, I have performed experiments to determine how to design features that provide unambiguous haptic cues as well as advantageous constraint forces.

1.2.3 One Degree-of-Freedom Environments

Two experiments were conducted for this study. The haptic interface used for both experiments was a one degree-of-freedom device, which is described in Chapter 4. The one degree-of-freedom device was used mainly because it was available in the laboratory. One advantage of its simplicity was that it exhibited very high performance (e.g. high force output, low inherent impedance). Moreover, using only one degree-of-freedom simplified the experimental design and data analysis. The main disadvantage was that results from one degree-of-freedom may not generalize well to more degrees-of-freedom.

1.2.4 Experiment I

In the first Experiment, subjects were asked to move the haptic interface from a starting position to a target position in minimum time. The speed and accuracy trade-offs in this type of task have been studied extensively for a century (see Chapter 3). In previous studies, however, vision guided subjects to the target. In our study, (usually) subjects had to find the targets using haptic perception alone.

The target regions were made perceptible by simulating different levels of damping depending on whether the handle was inside or outside the target region. In other words, the handle damping changed instantaneously when subjects passed into or out of the target region. Performance of the task was presumed to be determined by perception of the target, and also in part by mechanical constraints provided by the step changes in damping.

The goal of the study was not to examine speed accuracy trade-offs, but to study the relationship between step changes in damping and performance of a simple, yet representative positioning task.

1.2.5 Experiment II

The results of Experiment I indicated that haptic perception probably had a greater influence on performance than did the constraint forces. Also, many questions about the relationship between certain environment parameters and haptic perception were left unanswered. For these reasons, Experiment II dealt only with haptic perception and did not require subjects to perform a positioning or manipulation task. Subjects were asked to detect haptic features which were simulated using combinations of linear stiffnesses. The features were similar to the detent and puncture simulations shown in Figure 1.3.

1.2.6 Original Elements of the Thesis

Significant differences between this work and previous work are: the focus on perception of discrete haptic features, and the incorporation of manipulation and haptic perception in one task. Many studies of haptic perception via haptic interface devices have focused on discrimination of linear impedances (e.g. masses, springs, dampers). While these results are important, I would argue that the perceptions which can be created with non-uniform environments are of much greater significance for the goal of creating useful haptic simulations. Texture simulation is another important aspect of haptic environments, which is not addressed in this thesis. A central focus in this thesis was the influence of mechanical constraint on human manipulation, which has not been addressed in any systematic way in the literature. Related research will be reviewed more thoroughly in Chapter 3.

1.3 Organization of the Thesis

Chapters 2 and 3 are also introductory. Chapter 2 provides a concise review of psychophysics and psychophysical methods for studying perception. Chapter 3 is a survey of related literature in the areas of haptic perception and aimed movement studies. Chapter 4 describes the haptic interface that was used in the experiments and includes the results of a number of quantitative performance tests. Chapters 5 and 6 are the presentations of Experiments I and II respectively. Chapter 7 summarizes the results of the two experiments and offers concluding remarks on the relevance of this work for the larger project of developing haptic display systems. Chapter 7 also describes plans for future work.