Chapter 2

Related Work

2.1 Haptic Feedback in Music Controllers

The enhancement of computer-based instrument interfaces with haptic feedback dates back to the late 1970s, when Claude Cadoz and his colleagues at the Association pour la Cration et la Recherche sur les Outils d'Expressions (A.C.R.O.E.) built an experimental device that relayed forces, mapped to some aspect of a sound synthesis model, back to a user's hand by means of a motorized joystick (Cadoz *et al.*, 1990; Gibet and Florens, 1988). The development of their subsequent series of experimental devices, which they call "gestural gorce-feedback transducers," is predicated on the realization that the physical instrument-performer relationship is bidirectional, i.e., the performer both transmits information to the instrument in the form of gestures, and receives information back from the instrument in the form of tactile/kinesthetic feedback. Further they suggest that in many cases, the instrumental gesture is the best way to communicate appropriate sound control parameters. Their system therefore exploits a modular design in which the gestural controller (with its appropriate force-feedback) can be associated with any sound synthesis model not through direct manipulation of synthesis parameters but rather by mappings between synthesis parameters and the so-called "instrumental gestures" that would cause them (see Chapter 1). In a similar study, Gillespie (1996) built a one-octave force-feedback piano keyboard to convey forces derived from this model to the player's hand. Whereas Cadoz's system derives the forces relayed to the player from aspects of the sound synthesis model being controlled, Gillespie derived his force feedback directly from the mechanics of the instrument's action.

A second approach to designing music controllers with haptic feedback has been to use actuated exoskeleton or glove-based devices. Such devices act as a mediating layer between the hand and its environment, simulating forces and vibrations as the hand contacts virtual objects in space. Bongers (1994) attached "muscle wire" to a glove controller, using the wire to constrain the flexibility of the fingers. He incorporated this controller into a performance environment where the player could feel the path of a sound as it traveled through space. Chu (1996) also proposed a haptic MIDI controller for localizing sound. Citing psychophysical studies by Gescheider *et al.* (1975), Frost and Richardson (1976), and Richardson and Frost (1979), Chu pointed out that the haptic system is well suited to processing spatial information relayed via vibrotactile simulators and, for low-frequency sounds, can actually surpass the auditory system.

Rovan and Hayward (2000) explored the perceptual attributes of a simple vibrotactile vocabulary synthesized in response to a gesture using a glove with vibrotactile feedback. Their system, called "VR/TX," relayed a collection of tactile "sounds" whose perceptual attributes coincided with those of the auditory material being manipulated. The goal of this work was to augment performance on so-called "open-air" controllers — controllers with no direct mechanical coupling between player and instrument — by creating artificial tactile feedback.

Other studies have examined the use of vibrotactile feedback to relay components of a synthesis model back to the performer via touch. Chafe (1993) used the audio output from a physically-based model of a bugle to relay vibrations associated with resonant modes back to a player's lips.

As we have shown elsewhere (Chafe and O'Modhrain, 1996), the relationship between haptic and auditory cues need not be based on the behavior of a known musical instrument. With an eye toward incorporating haptic feedback into interfaces for sound-editing applications, we recorded two different performances of the opening bars of a Beethoven piano sonata and derived a parameter that described the increase and decrease of musical "tension," as projected by two experienced pianists. We then mapped these changes in musical tension to changes in stiffness of a virtual wall so that, as the music progressed, it was possible to "feel" the expressive contour imposed by the player — in effect to intercept the player's performance gestures. We wanted to discover whether being able to observe the movements which gave rise to musical nuances would enable a third party, such as a record producer or editor, to better match expressive contours in editing within musical phrases. An informal pilot study with experienced musicians suggested that differences in phrase contours between players could be perceived haptically. All felt that this form of feedback would enrich interfaces for music-editing applications.

Though these studies suggest that haptic feedback could improve the quality of the experience of playing virtual instruments, none has provided empirical evidence for the utility of haptics in music applications. The experiments presented in this dissertation were therefore carried out to provide some measures for assessing the potential for haptic feedback in improving control of computer-based instruments.

2.2 Haptic Feedback in Human-Computer Interaction

2.2.1 Enhancing Virtual and Telepresence Environments

Evidence that computer-generated haptic feedback can improve performance of manipulation tasks in virtual or telepresence environments is provided by several recent studies in the fields of human-computer interaction and telemanipulation. Hasser *et al.* (1998) reported two experiments showing that active force feedback can significantly improve performance in moving to and clicking on screen targets. Their results show that the addition of force feedback improved targeting performance by 61 percent with a decrease in targeting errors of 70 percent. In a second study, (Dennerlein, 2000), force feedback was also shown to improve performance in a steering task where participants were required to navigate through tunnels with increasing indices of difficulty. These tasks simulate the processes by which menu items are located, and require both horizontal and vertical screen movements of the cursor. Movement times were on average 52 percent faster when force feedback was present, compared to performance with a conventional mouse.

In his ground-breaking work, Rosenberg (1994) demonstrated that incorporating virtual objects or "fixtures" into telepresence environments to act as guides or tools for the operator could significantly improve performance in telemanipulation tasks. In his study, operators performed a peg-insertion task under three different conditions — direct manipulation, telepresence, and telepresence environments enhanced with virtual fixtures. Results confirmed that human performance when directly manipulating objects was far superior to telemanipulation. However, results also showed that the use of 3-D haptic overlays or fixtures could improve performance of a standard peg-insertion task by as much as a factor of two. In a further series of telemanipulation studies, Kontarinis and Howe (1995) showed that relaying high-frequency vibrations to an operator's hand significantly improved performance of a simple manipulation task. Using a planar teleoperated hand, operators grasped a passive stylus. Performance with and without high-frequency feedback to the operator's hand was compared. Results showed on average an increase in performance of a factor of 1.8 when vibrotactile feedback was present. Taken together, these studies indicate that including feedback to the haptic senses in manipulation tasks can significantly improve performance of those tasks. Given this, Experiments I and II were carried out to discover whether adding haptic feedback to a virtual musical instrument would produce equivalent gains in performance when manipulating not icons or objects, but sound (see Chapter 4).

2.2.2 Simulating Real Environments

Another area of research that has benefited from haptic feedback technology is training simulator design. If skills learned in a simulator are to transfer to an equivalent real-world environment, then all aspects of that environment, including its "feel," must be rendered as accurately as possible (see Schmidt and Lee, 1999, chapter 14).

Because high-fidelity haptic simulation inevitably requires more costly display technology, simulators that incorporate haptic feedback are still mainly found in fields such as flight simulation and simulation of surgical procedures, where the costs of their development are far outweighed by the benefits of off-line training. Within these contexts, the addition of computer-generated haptic feedback can significantly enhance the "realism" of the environment. Simulators for training students in techniques such as endoscopy (Bockholt *et al.*, 1999) and laparoscopy (Tseng *et al.*, 1998) are now routinely used. Kaufmann *et al.* (1998) have shown that it is possible for a surgeon situated in a remote location to augment instruction in anatomy, surgical principles and adjunct surgical techniques for inexperienced students working in the operating room. Using a force feedback display, the surgeon can vicariously feel anatomical structures and point out features such as texture and tissue mas to the student.

Flight simulation, too, has long contributed to haptic simulation research. Repperger *et al.* (1997) examined the efficacy of a force-reflecting joystick to improve pilots' performance during a simulated landing task in wind turbulence. Repperger found that the addition of force characteristics to the joystick that simulated the "feel" of turbulence significantly improved performance, resulting in less effort for control and lower subjective workload.

2.2.3 Augmented Feedback

Another area where haptic feedback has been shown to significantly enhance performance is the learning of motor tasks. Unlike full-blown simulators, these studies single out elemental components of a task and guide the student's hand or body by simulating the forces, torques and movement trajectories associated with successful completion of the task. In the early stages of learning, such augmented feedback can reduce the time spent by the student in discovering correct strategies for task completion (see Chapter 3 for further discussion of the role of feedback in the stages of skill acquisition). Henmi and Yoshikawa (1998) recorded the position and force trajectories of a calligraphy teacher's writing-brush strokes and then displayed these trajectories to a student using a haptic display device. The goal of the system was to pass on to the student a feel for the teacher's horizontal brush trajectory, the normal force against a virtual sheet of paper and the distance between the teacher's brush and the virtual page. Recognizing that it is impossible to display both the normal force information and the normal position information at the same time, the authors implemented two methods of skill display, one to display position trajectories and the other to display related force information. In a similar study, (Gillespie *et al.*, 1998), we explored paradigms for teaching manual skills using haptic display devices under computer control. Like a virtual fixture, our "virtual teacher" was intended to act as an aide or to facilitate task execution, but unlike the virtual fixture, the teacher is present only during training periods. The virtual teacher's objective, implicitly understood by the user, is to promote independent mastery over the task. In a pilot study, a robot taught participants successful strategies for performing a crane-moving task. Here a real crane was suspended from a cable that was driven by a closed-loop controller. Initial results indicate little difference in learning times for participants, though much work still needs to be carried out on the haptic display device itself.

Whereas virtual teachers seek to impart skills that students can carry from a virtual environment into the real world, games and sport simulations are designed to promote transfer of real skills to a virtual environment. Kawamura *et al.* (1995), for example, has developed a wire-based haptic display with six degrees of freedom, where force and torque vectors related to the trajectory of a tennis ball are relayed to the player's hand. Results of a preliminary study indicate that experienced players carried skills learned by playing real tennis into the virtual environment.

Perhaps the most compelling test for any virtual teaching environment is whether experienced practitioners will still out-perform novices. If so, then those elements of feedback that are necessary for successful completion of the task are presumed to be present in the simulation. O'Toole *et al.* (1998) conducted a study in which experienced surgeons and novices performed a virtual suturing task. Results indicate that experienced surgeons performed better than inexperienced medical students, but that students improved more rapidly with practice. Insofar as that study examined the expert's ability to bring skills learned in the real world into a virtual environment, the study most closely parallels the goals of the final experiment presented in this dissertation (see Chapter 4, Experiment IV).

2.3 Summary

This chapter has reviewed haptic interaction design in the fields of music, human computer interaction, telepresence, simulation and skill transfer. In particular, the work presented here has examined the efficacy of adding haptic feedback to enhance performance of manipulation tasks. In this respect, these studies share a common goal — to support the acquisition and performance of manual skills in the environment of human-computer interaction. In Chapter 3, we change perspective, examining the acquisition of motor skills from the point of view of the human motor system. Our hypothesis is that an understanding of how the human motor system represents the dynamic properties of its environment will provide a framework for more effective haptic interaction design.