6.3 Summary and Expectations

Tactile and force feedback provide important sensory modalities that are prerequisites for many types of practical VE applications. Without these modalities, applications that require complex or precise interactions with the environment, or between users who are not physically present in the same location, are not possible. As yet, however, haptic interface technology can support only very limited types of tactile and force feedback.

Several groups of researchers are investigating the development and use of tactile feedback. Between them, they are addressing the ability of tactile displays to present contact force, slip, texture, vibration, and thermal sensations. Several prototype devices have been developed for experimental purposes and shown that these sensations, as least in primitive form, can be generated. For example, in tests using a blunt pin tactile displays, users were able to discriminate between simple patterns such as a point, line, and plane. Even so, research into tactile feedback is in its initial stages. By and large, current tactile displays provide sensations to a very limited area, usually the fingertip, and many of the approaches in use will not scale up to provide varying sensations over a larger area. A wide variety of actuator types are being employed, including shape memory alloy, pneumatic, electromagnetic, and piezo-electric technologies and no single technology appears capable of supporting all types of tactile feedback. While each actuator technology has its own particular limitations, they all suffer from relatively large physical dimensions that also constrain their practical use. Studies that identify the most pertinent types of tactile feedback for specific types of applications, and the most appropriate technology for displaying that feedback, are needed. One important practical issue must be to identify where and how trade-offs can be made between the tactile and force feedback modalities. Further evidence of the immaturity of tactile feedback technology is given by the absence of general software models that can be used to determine the sensations that need to be generated with respect to a particular interaction with the environment; with the exception of contact forces, work on developing such models has yet to start. Since tactile sensations depend on a range of physical properties (such as microscopic geometry, coefficient of friction, kinetic elasticity, and thermal conductivity), empirical studies will be important in determining the accuracy that needs to be modeled for practical representation of, for example, surface texture.

Much of the basic psychophysical information needed to support a tactile interface in VEs is available, although there are gaps that need to be filled. There is a lack of data, for example, on the human capability to detect different surface textures and complex patterns, and to detect object slip. The ability of current displays to meet human tactile thresholds for detecting contact, slip, pattern, vibration, and thermal sensations varies. The minimum bandwidth with which the human hand can perceive forces is 20-30 Hz and the majority of tactile displays meet this requirement. Pin-based displays are, in theory, capable of providing different patterns that can be sensed; since current devices have a pin tip of about 1 mm and pin spacing ranging from 1.5 to 3 mm, they meet or are close to the human thresholds for spatial resolution and the two-point limen. The maximum available pin array is, however, limited to 5 by 6 pins and this is insufficient for portraying any but the most simple patterns. In the case of vibration, displays seem to be evenly split between operating at low frequencies (<20 Hz) and mid-range frequencies (~200 Hz), this latter group being capable of presenting contact forces. While some experiments have shown the ability of at least one display to provide vibrations that support object manipulation, none approach the bandwidth recommended for supporting skillful manipulative tasks. In terms of frequency range, the largest range provided by any of the displays is 6 -100 Hz. Finally, the temperature displays are similar in providing a temperature resolution of 1°C which provides good support for the human JND. They vary in the range of temperatures that can be displayed with two out of the three displays capable of providing temperatures well in excess of what is likely to be needed, that is, temperatures beyond the human pain threshold.

Four tactile feedback products are commercially available. The *Cyber*Touch, Touchmaster, and the Tactools System provide tactile displays that are mounted on the user's fingertips to provide feedback on object contact. The Displaced Temperature Sensing System generates thermal feedback, again via displays in contact with the user's fingertips. Reflecting the immature status of this area, however, these products all are primarily display devices with a primitive software interface that requires the user to explicitly control the device. This first generation of products are best suited for use as research tools.

This is an relatively active area of research and much progress in addressing the issues outlined above should be made in the next few years. Even as research issues start to be resolved, practical problems in engineering and manufacturing small displays that can present tactile sensations to various hand and body areas may continue to limit practical use. With all these concerns in mind, it is unlikely that tactile feedback will come into widespread use in the next two to three years, though some initial practical use can be expected shortly thereafter. The switch to common use will be rapid, however, as soon as practical applications that demonstrate the value of tactile feedback appear.

As previously noted, the development of force feedback devices for use in VEs has greatly benefited from earlier work in providing force feedback for telerobotic applications. Accordingly, some parts of this interface technology are more mature than their tactile counterparts, although much progress is still needed.

The majority of current force feedback devices can be distinguished as exoskeleton devices that deliver forces to some subset of the shoulder, elbow, wrist, and finger joints; tool-based devices that deliver forces to the hand via a knob, joystick, or pen-like object held by the user; thimble-based devices that deliver forces to the user's fingertips; or robotic graphics systems that use real objects to provide forces to the hand. There are two exceptions to this categorization. Aura Systems, Inc. Interactor devices use low frequency sound vibrations to simulate force sensations that are presented to the user's torso, and the Rutgers Master delivers grasping forces to the hand via pneumatic micro-cylinders mounted on a glove. Exoskeleton devices have the advantage of allowing a user some freedom of movement in a VE, but are encumbering and their mechanical implementation may impose some restrictions on the joint movements. With the exception of the force feedback interfaces used in UNC's molecular docking and atomic force microscope, all the tool-based devices are desktop-based, thus constraining user movement. The desktop-based devices vary quite widely in the working space they support, ranging from only to few centimeters to a sphere of 40 cm diameter. The devices are primarily mechanical, driven by servo motor actuators. This technology present several problems, such as backdrivability and friction. The primary difficulty, however, is one of stability. The robotic graphics approach to providing force (and tactile) feedback is unencumbering and allows full user movement with a theoretically unlimited working space. Here the major issue is that of safety.

Among all these devices, eleven commercially available force feedback products have been identified. Since they are of very differing types and provide markedly different capabilities, each is suitable for different types of applications. Consequently, even ignoring performance characteristics, a prospective user is likely to have little choice among products. These systems are all expensive and most are developed to order, often with a significant delay before delivery. As yet, none of the available systems has seen significant practical use. This situation is likely to change in the very near future because the newly released PHANToM seems to be quickly becoming the system most commonly used by researchers.

In investigating how to evaluate the quality of force feedback systems, Rosenberg (1995) has proposed a set of minimum performance standards. While the necessary maximum force output and range of motion is application dependent, Rosenberg recommends a force output resolution of 12 bits, position resolution of 0.001 inch, and passive friction less than 1% of the maximum force output. Other requirements pertain to the system bandwidth (> 50 Hz), minimum sampling rate (2000 Hz), and latency (1 msec). Several systems meet some subset of these requirements, but currently only PHANToM meets them all (with the possible exception of sampling rate, information on which was not available). Data on kinesthetic human capabilities collected through experiments provide other measures by which to assess force feedback systems. In this case, most current devices are capable of supporting the human JND for force sensing and the representation of a solid object to the fingers. Most are not, however, capable of providing the forces needed to represent a solid, immovable wall.

The hardware limitations of force feedback devices constrain the fidelity with which real world interactions can be simulated. In particular, the accuracy of sensors, latency of computer, performance of actuators, different location of sensors and actuators, and transparency of mechanical transmission all play an important role. Any force feedback device must allow for variability in hand size, otherwise the resulting scaling up or down of the force applied on the fingers will lead to imperfect perception of the interaction forces. Additionally, the characteristics of a user's interaction can change dynamically and radically, resulting in a non-linear system. Representation of rigid objects is a particular problem and most systems exhibit contact instability near a hard surface. Current approaches to this problem either add viscosity, which usually means that the user feels resistance even in free space, or reduce the stiffness of the simulated surface, leading to a spongy feeling. Since many aspects of this stability problem are insoluble, further understanding of how to employ multi-sensory input and how to exploit limitations in the human haptic system to alleviate the problem are needed. Safety is an example of another issue that needs further investigation. This is a concern that arises when there is a need to for the device to exert forces to oppose a user's volitional movements and safeguards are required to ensure that a computer or device malfunction does not result in user injury.

The software support required to implement force feedback interfaces is just starting to receive significant attention. Ad hoc force models to compute and generate forces have been developed by different researchers for use as research tools for quite some time. Now a few researchers are looking at looking at more general purpose model frameworks and developing techniques for more efficient haptic rendering. The work by Dr. Salisbury and his colleagues at MIT is notable in this area. Nonetheless, as force feedback devices continue to be developed, the lack of adequate software support remains a limiting factor in overall force feedback interface technology.

Another shortcoming lies in the understanding of human kinesthetics. While some investigation of human haptics with respect to the use of force feedback in VEs has been conducted, much more is needed. General issues in the areas of the biomechanical, sensorimotor, and cognitive abilities of the human kinesthetic system need to be investigated to provide better support for the hardware and software design of these interfaces.

As indicated above, current force feedback interface systems are severely limited in the types of force sensations they can deliver. Accordingly, within the next two to three years, the use of force feedback interface in practical applications is expected to be infrequent and mainly limited to a few application domains where the provision of force feedback is critical, such as surgery. Since many such applications will require special-purpose force feedback interface systems, new force feedback systems will continue to be developed. It is important to note, however, that although the current types of force feedback devices are likely to serve valuable roles in certain specialized applications, the approaches being taken are incapable on being scaled up to provide forces that more fully support the possible range of human interactions with a VE. Today, only the robotic graphics approach has the potential for such flexibility, and this is still the subject of feasibility studies. d