6. HAPTIC INTERFACES

The human haptic system has an important role to play in human interaction with VEs. Unlike the visual and auditory systems, the haptic sense is capable of both sensing and acting on the environment and is an indispensable part of many human activities. In order to provide the realism needed for effective and compelling applications, VEs need to provide inputs to, and mirror the outputs of, the haptic system. Inputs to the haptic system are in the form of haptic displays and outputs are motor action commands, where the primary input/output variables are displacements and forces.

Haptic sensory information is distinguished as either tactile or kinesthetic (sometimes called prioreceptive) information. The difference between these is best illustrated by example. Suppose the hand comes up to an object suspended in space. The initial sense of contact is provided by the touch receptors in the skin, which also provide information on the contact surface geometry, the surface texture of the object, and slippage. When the hand applies more force, kinesthetic information comes into play providing details about the position and motion of the hand and arm, and the forces acting on these, to give a sense of total contact forces, surface compliance, and (if the hand is supporting the object in some way) weight. In general, of course, tactile and kinesthetic sensing occur simultaneously.

In order for the hand to manipulate the object, say move it horizontally, rotate it, or pinch it, the haptic system must issue motor action commands that exert forces on the object. These forces are highly dependent on the type of grasping that is used. Power grasping employs all the fingers and the palm, whereas precision grasping uses only the fingertips. Which is appropriate in a specific circumstance depends on such factors as the forces to be exerted and the dexterity of manipulation required. The manner in which the object being manipulated responds depends on the laws of physics and, potentially, a host of other sciences. That response, however, will be signalled by the haptic senses and may, in turn, guide further manipulation.

These, then, are the types of capabilities desirable for VEs and topics of this section. However, the following discussions are limited to consideration of the human hand, arm, and torso. Issues pertaining to whole body movement are addressed in Section 7.

6.1 Tactile Interfaces

As indicated above, tactile sensing plays an important role in object discrimination and manipulation. In many situations, it is either indispensable or critical for task performance. For example, there are reports of surgeons performing laparoscopic surgery who find the visual feedback of laparoscopic instruments insufficient and insert a finger into the skin opening to feel for the presence of tumors in underlying body tissue. The fact that the lack of tactile feedback makes certain tasks more difficult is substantiated by experiments performed by Massimino and Sheridan (1993). Additional experiments have demonstrated the value of tactile feedback, for simple tracking tasks (Patrick, Sheridan, and Massimino, 1990), for reaction time reduction in target pointing (Akamatsu, 1994), and in degraded visual conditions (Massimino and Sheridan, 1993). While the presence or absence of tactile sensing undoubtedly has an impact on the sense of immersion experienced by VE users, there are no known studies that have investigated this.

In addition to the obvious example of sensing environment or object temperature, tactile sensing can support many discrimination activities that force sensing cannot. Tactile sensing, for example, is needed to determine the local shape and texture of objects and for detecting slip. It also provides information on surface compliance, elasticity, viscosity, and electrical conductivity. While the tactile ability to sense vibration is critical for determining surface texture, it is also valuable in its own right. Sensing of high frequency vibrations is a major component of many tasks and, in some cases, detection of vibration can be the goal of the work. Kontarinis and Howe (1995), for example, have shown that the presentation of high frequency vibrations can enhance performance of certain tasks by reducing reaction times or permitting minimization of applied forces. Since force feedback does not occur prior to any surface deformation, tactile sensing is also required for initial contact detection. Massimino and Sheridan (1993) have shown that tactile feedback can provide a significant performance improvement over force feedback for detecting the presence of contact forces, and tactile feedback provides similar, or superior, performance for detecting the magnitude of contact forces and for tracking a sustained contact force. Lastly, Howe (1992) has shown that tactile feedback is a necessary support to force feedback when gauging the minimum forces necessary for precise manipulation tasks.

It is also useful to note that, in some circumstances, one type of tactile display can be substituted for another. For example, Ino et al (1993) showed that temperature displays can be used to support discrimination of object materials and Morgan (1965) uses such a display to create the sensation of pressure or object contact.

At the current time, no known VEs in practical use support a tactile interface (the term “practical use” refers to systems either commercially available or those in everyday use by users, as opposed to developers.) By default, these systems use visual and/or auditory senses to substitute for the tactile sense; for example, by sounding an auditory tone when the user comes “in contact” with a virtual object.

Tactile stimulation can be achieved in a number of different ways. Those being used for VE systems include mechanical pins activated by solenoid, piezoelectric crystal, and shape-memory alloy technologies, vibrations from voice coils, pressure from pneumatic systems, and heat pump systems. The major strengths and weaknesses of these different approaches are summarized in Table 11. Other technologies, such as electrorheological

Table 11. Tactile Feedback Actuator Technologies[a]

Technology	Description	Advantages	Disadvantages
Piezoelectric crystals	Changing electric fields causes expansion and contraction of crystals	- High spatial resolution	- Restricted to resonant frequency
Pneumatic	Takes many forms. As air-jets, provides an array of air nozzles that can be gated to a display pattern. As air-rings (cuffs), like miniature blood pressure cuffs. As bladders (bellows), often the size of a finger pad and held against the finger by a glove or band. As an array of tiny pressurized bladders, many to a single finger pad.	- Low mass on hand	- Poor spatial and temporal resolution - Limited bandwidth
Shape Memory Alloy	SMA wires and springs contract when heated and expand again as they cool under stress	- Good power-to-mass ratio	- Low efficiency during contraction - Heat dissipation problems limit relaxation rate of wires
Solenoid	Magnetic coil applies force to ferrous plunger	- High steady-state forces - Better bandwidth than other materials (except for piezoelectric crystals and voice coils)	- Relatively heavy - Nonlinear, can require extra effort to control
Voice coil	Voice coil vibrates to transmit low amplitude, high frequency vibrations to the skin.	- High temporal resolution - Relatively small, does not obstruct normal movement ranges of the fingers	- Poor spatial resolution - Limited scalability
Heat pump	Solid state device that moves thermal energy to heat or cool the skin	- No fluids required	- Poor spatial and temporal resolution - Bulky - Limited bandwidth

a. Based on Hasser (1995, 1996)

fluids that harden under the application of an electric field also are under investigation. Additional technologies found in medical applications, such as electrotactile and neuromuscular stimulation, have not yet been used and their invasive nature makes future use unlikely.

6.1.1 The Human Tactile Sense

There are four kinds of sensory organs in the hairless skin of the human hand that mediate the sense of touch. These are the Meissner's Corpuscles, Pacinian Corpuscles, Markel's Disks, and Ruffini Endings. As shown in Table 12, the rate of adaptation of these receptors to a stimulus, location within the skin, mean receptive areas, spatial resolution, response frequency rate, and the frequency for maximum sensitivity are, at least partially, understood. The delay time of these receptors ranges from about 50 to 500 msec.

Table 12. Functional Features of Cutaneous Mechanoreceptors[a]

Feature	Meissner Corpuscles	Pacinian Corpuscles	Merkel's Disks	Ruffini Endings
Rate of adaptation	Rapid	Rapid	Slow	Slow
Location	Superficial dermis	Dermis and subcutaneous	Basal epidermis	Dermis and subcutaneous
Mean receptive area	13 mm^2	101 mm^2	11 mm^2	59 mm^2
Spatial resolution	Poor	Very poor	Good	Fair
Sensory units	43%	13%	25%	19%
Response frequency range	10 - 200 Hz	70 - 1,000 Hz	0.4 - 100 Hz	0.4 - 100 Hz
Min. threshold frequency	40 Hz	200-250 Hz	50 Hz	50 Hz
Sensitive to temperature	No	Yes	Yes	At > 100 Hz
Spatial summation	Yes	No	No	Unknown
Temporal summation	Yes	No	No	Yes
Physical parameter sensed	Skin curvature, velocity, local shape, flutter, slip	Vibration, slip, acceleration	Skin curvature, local shape, pressure	Skin stretch, local force

a. Adapted from (Shimoga, 1993b), (Bolanowski et al, 1988), (Kontarinis, 1993), and (Reynier and Hayward, 1993).

It is important to note that the thresholds of different receptors overlap, and it is believed that the perceptual qualities of touch are determined by the combined inputs from different types of receptors. The receptors work in conjunction to create an operating range for the perception of vibration that extends from at least 0.04 to greater than 500 Hz (Bolanowski et al, 1988). In general, the thresholds for tactile sensations are lowered with increases in duration. Skin surface temperature can also affect the sensitivity of sensing tactile sensations.

These details provide some initial guidance for the design and evaluation of tactile display devices in such areas as stimulus size and duration, and signal frequency; perhaps constraining the type of display technology used. For example, Kontarinis and Howe (1995) note that the receptive areas and frequency response rates indicate that a single

vibratory stimulus for a fingertip can be used to present vibration information for frequencies above 70 Hz, whereas an array-type display might be needed for the presentation of lower frequency vibrations.

Additional information is available when looking at a higher level that the receptors just discussed, that is, at the receptivity of the skin itself. The spatial resolution of the fingerpad is about 0.15 mm, whereas the two-point limen is about 1 to 3 mm. Detection thresholds for features on a smooth glass plate have been cited as 2 μm high for a single dot, 0.06 μm high for a grating, and 0.85 μm for straight lines. Researchers have also looked at the ability to detect orientation. The threshold for detecting the direction of a straight line has been measured at 16.8 mm. When orientation is based on the position of two separate dots, the threshold was 8.7 mm when the dots were presented sequentially, and 13.1 mm when presented simultaneously. Reynier and Hayward (1993) discuss these findings and the results of additional work in this area. Data on the temporal acuity of the tactile sense is also reported by these researchers, who note that two tactile stimuli (of 1 msec) must be separated by at least 5.5 msec in order to be perceived as separate. Although, in general, increases in tactile stimulus duration can lower detection thresholds.

In a set of psychophysical experiments that investigated the capability of the human fingertip to detect strain, Ino (1993) found that the stimulus threshold was highly dependent on the motion of the skin contact surface (velocity, direction, and rotation), and surface viscosity and temperature, though not greatly affected by surface roughness. The reported findings are shown Table 13.

Table 13. Stimulus Thresholds for Strain

Stimulus	Threshold	Rate of Change
Velocity	50 μm at 0.2 mm/sec decreasing to 20 μm at 4 mm/sec. Threshold is related to direction as longitudinal < slant < transversal (in particular, threshold at 1 mm/s in longitudinal direction is ~0.5 that in trans. direction)	-13 dB/dec transversal, -11 dB/dec slant, -6 dB/dec longitudinal
Rotation	0.046° at angular velocity of 21.6°/sec, increasing to 0.265°at 0.72°/sec	-9 dB/dec
Surface Viscosity	500 μm displacement detectable at 233 μm/s for viscosity of 500 cSt, decreasing to detection at 986 μm/s for 30,000 cSt	6.9 dB/dec
Surface Roughness	35 μm for average grain size of 75 μm, increasing to 41 μm as grain size decreases to 8.5 μm	-
Surface Temperature	Minimum when contact surface near 32°, increasing with temperature	-

Burdea and Coiffet (1994) have summarized what is known about the human hand sensing bandwidth, as reproduced in Figure 64. Additional details are available with respect to vibration. The human threshold for detection of vibration at about 28 dB (relative to 1 μm peak) for frequencies in the range 0.4 - 3 Hz, this decreases for frequencies in the range of 3 to about 250 Hz (at the rate of -5 dB/octave for the range 3 - 30 Hz, and at a rate of -12 dB/octave for the range 30 - 250 Hz), for higher frequencies the threshold then increases (Shimoga, 1993b).

Figure not available for electronic version.

Figure 64. Human Hand Sensing Bandwidth

Reprinted by permission of John Wiley & Sons, Inc. and IEEE.

The literature also provides information on the just-noticeable-difference (JND) for changes of temperatures. Researchers Yarnitsky and Ochoa (1991) conducted experiments that looked at the JND of temperature change on the palm at the base of the thumb. They found that two different measurement methods gave different results, and the difference between results increased as the rate of temperature change increased. Using the more traditional measurement approach based on a method of levels, and starting at a baseline temperature of 32°C, the rate of temperature change (1.5, 4.2, and 6.7°C/sec) had no detectable effect on the JND for warming temperatures (~0.47°) or cooling temperatures (~0.2°). Subject reaction time was independent of the method used, and also independent of the rate of temperature change, although the reaction time for increases in warming (~0.7°) was significantly longer than the reaction time for increases in cooling (~0.5°). In reviewing work in this area, Zerkus et al (1995) report on findings that the average human can feel a temperature change as little as 0.1°C over most of the body, though at the fingertip a sensitivity of 1°C is typical. He also states that the human comfort zone lies in the region of 13 to 46°C. LaMotte (1978) reports that the threshold of pain varies from 36 to 47°C depending on the locus on the body, stimulus duration, and base temperature.

6.1.2 Commercially Available Interface Devices

Currently, few tactile interface devices are commercially available. EXOS, Inc. market the Touchmaster that is intended to present a sense of object contact to the user. It can be used independently or with their Dextrous HandMaster (see Section 5.1.2.3 for a discussion about the Dextrous HandMaster). Additionally, EXOS, Inc. sells a Hand Exoskeleton Haptic Display (HEHD) that provides both tactile and force feedback displays to the hand. Since the HEHD uses the same tactile display as the Touchmaster, it is not discussed in detail here, but more information is available in the section on commercially available force feedback interface devices (Section 6.2.2.6). Xtensory, Inc. market the Tactool system that also provides object contact feedback. A very different device, the Displaced Temperature Sensing System (DTSS), is marketed by CM Research, Inc. to provide temperature feedback. The characteristics of these products are summarized in Table 14 and they are discussed in more detail in the following subsections.

Until recently, Intelligent Systems Solutions, UK, (formerly the Advanced Robotics Center), marketed a tactile interface device based on pneumatic technology. A multi-channel pneumatic controller that included a pump, reservoir, and proportional pressure control channels was used to inflate air pockets that were designed to mount on existing, commercially available gloves. The resulting product was called the Teletact Glove and provided both tactile and force sensing. In its final version, the Teletact Glove used 30 air pockets with 2 pressure ranges. Twenty nine of these air pockets were positioned along the fingers and capable of a maximum pressure of 15 psi. The remaining air pocket was positioned in the palm and capable of 30 psi. Problems such as the deterioration of the air pocket material over relatively short periods, and a change in company focus, led to the product being withdrawn from the market.

Finally, for those interested in developing their own tactile interface device, or just experimenting with the tactile technology, Xtensory, Inc. and TiNi Alloy Co. both market tactile display kits based on SMA technology. Xtensory's Tactool Experimenter product, priced at $250, consists of a single tactor with parts and a circuit diagram, and assembly is required. TiNi Alloy's Tactor Demonstration Kit provides a single 9 x 20 x 2.5 mm tactor, pocket-sized Driver Box, interface cable for a PC-type serial port, and demonstration program. This tactor uses Muscle Wires constructed of Nitinol. With less than 1 volt, the

Table 14. Characteristics of Commercially Available Tactile Displays

Product	Vendor	Position of Display(s)	Type of Actuator	Effect	Tactile Sensation	Price
*Cyber*Touch	Virtual Technologies, Inc.	4 fingers, thumb, and palm	(Proprietary)	Vibration (0-200 Hz)	Object contact	$14,800
TouchMaster	EXOS, Inc.	4 fingers and thumb	Voice coil	Vibration (210-240 Hz)	Object contact	Contact vendor
Tactool System	Xtensory, Inc.	2 fingers	Blunt pins driven by SMA	Impulsive (30 g), vibration (20 Hz)	Object contact	$1,500
Displaced Temperature Sensing System	CM Research, Inc.	Via thimble	Thermoelectric heat pump	Temperature change	Heating/cooling	$10,000

tactor can pulse up to 2 cycles/sec on the skin to indicate contact with a virtual object, and variable pulse rates can be used to provide a sense of force feedback. The Tactor Demonstration Kit is priced at $178.

6.1.2.1 *Cyber*Touch

Released only in December 1995, the *Cyber*Touch product from Virtual Technologies, Inc. provides a tactile feedback option for the *Cyber*Glove (see Section 5.1.2.2). Tactile stimulators are attached to each fingertip and the user's palm to provide pulses or sustained vibration; they can be used individually or in combination to produce synchronized tactile patterns. The frequency of vibration generated is under user control and ranges from 0-125 Hz. Virtual Technologies, Inc. has applied for a patent on the actuator technology used and details of how the feedback is generated are not presently available. A photograph of Virtual Technologies' *Cyber*Touch vibrotactile feedback option for the 18-sensor *Cyber*Glove is shown in Figure 65, along with some specification details.

Specification	
Operation Modes	Vibratory
Bandwidth	0 - 125 Hz
Stimulator Dimensions	Approx. 1.5 - 0.5 in
Stimulator Weight	0.2 oz
Interface	RS-232 up to 115.2 baud

Photo courtesy of Virtual Technologies, Inc.

Figure 65. *Cyber*Touch

A separate product, the *Virtual*Hand Toolkit, provides a library of software routines that support use of *Cyber*Touch including, for example, routines that update the stimulator actuators. *Cyber*Touch itself comes with seven demonstration programs (including source code) that provide different force patterns. An additional demonstration shows the use of the tactile feedback in manipulating two balls, one suspended from a pendulum and the other resting on a simulated beach. *Cyber*Touch, with a *Cyber*Glove, is available for an introductory price of $14,800. Upgrade or trade-in options are available for users who have previously purchased a *Cyber*Glove. Also as part of the introductory promotion, the "Glove Mate" program provides a 34% discount towards the purchase of a second *Cyber*Touch glove to allow tactile feedback to both hands.

6.1.2.2 TouchMaster

The EXOS, Inc. TouchMaster provides a tactile display to the tips of all four fingers and thumb using voice coil actuators. These actuators provide vibrotactile feedback that can be used to represent information about object contact. The voice coils are mounted on a cable assembly and attached to the fingertips using velco bands, and driven by a signal condition box that can be interfaced to PC, VME, or other standard digital I/O busses. The standard configuration provides a fixed frequency of about 210 - 240 Hz at a constant amplitude, but optional variable frequency and amplitude electronics are available. Further details are given in Figure 66. The Touchmaster is built to order and price information is not available.

Specification

Operation Modes	Vibratory
Bandwidth	210 Hz
Display Dimensions	1 L x 0.75 W x 0.375 H in
Display Weight	0.2 oz
Interface	PC, VME or other standard digital I/O card

Photo courtesy of EXOS, Inc.

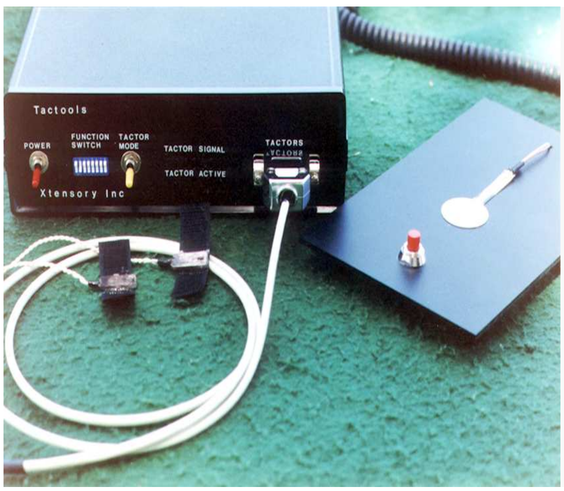
Figure 66. TouchMaster

In one experiment that investigated the effectiveness of the tactile display, researchers at EXOS, Inc. compared the use of a visual display (presented on a PC screen), the TouchMaster tactile display, and both visual and tactile displays in a task where subjects were asked to minimize the error in positioning of both thumb and index finger relative to the opposite sides of a virtual wall. The thickness of the wall was varied at 1.0 or 0.5 Hz between 30 mm and 80 mm. Data was collected from about 200 trials with each display combination and analyzed using a pairwise t-test. The results showed that trials with the visual display alone achieved an average error about two-thirds that produced with the tactile display alone, but the combination of both visual and tactile displays gave a performance increase over the visual display alone. Tactile feedback provided a five-fold improvement in the mean tracking error compared to the performance without tactile feedback.

In a second experiment, the difference between tactile and force displays as adjuncts to a visual display were investigated. (A 6 DOF Argonne E-2 master-slave manipulator was used to provide force feedback.) In this experiment, the subjects were asked to tap two targets alternately, as quickly as possible. The targets were of fixed width and set apart at three different distances, and an index of difficulty for each task was calculated based on this distance. For each index of difficulty, the results showed that the addition of either tactile or force displays to the visual display reduced task time by about one third. (The benefit of force feedback over that of tactile feedback depended on the task difficulty, ranging from 2% for the easiest task to 19% for the most difficult task.)

6.1.2.3 Tactool System

Xtensory, Inc. market the Tactool System where, again, the tactile display (called a tactor) is attached to a cable assembly for mounting on fingertips. While customizations are available, the base product consists of a single tactor (with associated cables) and a controller. The controller, which can support up to 10 tactors, provides the interface allowing the application software to give commands to “fire” a tactor. The primary interface is serial EIA232, but parallel, analog and MIDI interfaces are available to support such functions as reading sensors or daisy-chaining multiple Tactool Systems. Details on the tactor, Tactor Model XTT1, are given in Figure 67. This figure also shows a photograph of the Tactool System, together with a single pad-mounted tactor. The base Tactool System is priced at $1,500, additional tactors are available at $100 each. In addition, input sensors, which can be switches or force sensors, can be used for telerobotic applications.



Tactor Model XTT1 Specification

Pin Tip	1 mm
Pin Spacing	3mm for arrays
Rise Height	3 mm
Rise/Fall Time	0.05 sec
Pin Controllability	Individually addressable
Operation Modes	Impulsive, vibratory
Force	30 g
Bandwidth	20 Hz
Weight	4 gm
Display Dimensions	0.35 x 0.80 x 0.20 (in)
Interface	Serial EIA232

Photo courtesy of Xtensory, Inc.

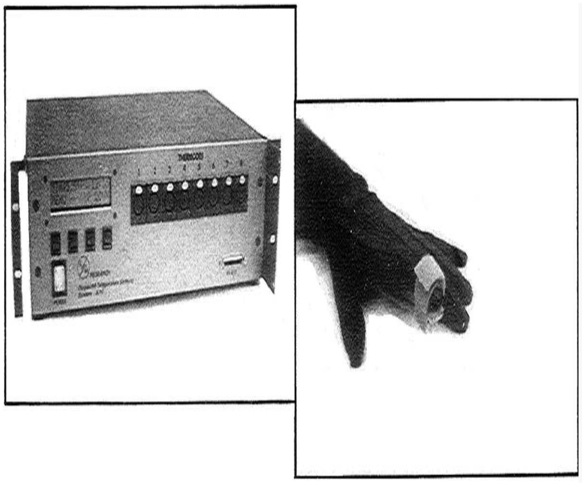
Figure 67. Tactools System

Xtensory also market a 5 x 6 pin tactor array not intended for fingertip use.

6.1.2.4 Displaced Temperature Sensing System

The only known commercial product that provides temperature feedback for VEs is the Displaced Temperature Sensing System (DTSS) marketed by CM Research, Inc. Specifically designed for VE applications, when used with some tracking device, this system allows a temperature appropriate for the user’s location in the VE to be sensed by the user’s fingers. Using a thermode (an assembly of a thermoelectric heat pump, temperature sensor, and a heat sink), DTSS takes feedback from the sensor and regulates the temperature of the thermode surfaces.

The current product, DTSS Model X/10, is intended as a research tool. It consists of a controller, eight thermodes and connecting cabling. The controller can support eight thermode channels, each of which can be programmed as an input or output channel. It can be operated directly from the controller unit or, via a serial interface, by computer. Analog inputs can be accommodated to allow tracking signals from external devices. The control law used for closed loop control of thermode temperature is the Proportional Integral Derivative law and the gains of each component in the law are adjustable. Safety features include large surface area heat sinks (the temperature of a heat sink is prevented from exceeding 40°C), and both a non-computer safety circuit and redundant software. DTSS is available for $10,000, with additional thermodes priced at $600 each. Further details are given in Figure 68. The initial version of DTSS, as shown in the figure, used velcro bands to attach ther-



Specification

Temperature Range	10-45° C
Temperature Resolution	0.1° C
Bandwidth	10 Hz
Display Weight	6 oz
Interface	RS-232

Photo courtesy of CM Research, Inc.

Figure 68. Displaced Temperature Sensing System

modes to the user's fingers. This has been replaced in the current system by a thimble-type unit that the user can insert his finger into. The system comes with demonstration software (including source code) for PC and Mac platforms.

CM Research is currently developing a further version of DTSS that will use liquid cooled thermodes. These thermodes will provide better heat dissipation and, hence, support more rapid changes in temperature feedback.

6.1.3 Current Research and Development

Until the last few years, the majority of research and development on tactile interfaces focused on the development of reading aids for the visually impaired (see, for example, (Sherrick, 1984), (Shimizu, 1986), (Barfield and Furness, 1995)), tools to support investigation into the human tactile sense (see, for example, (Cholewiak and Sherrick, 1981), (Schneider, 88)), tools to support hand rehabilitation (see, for example, (Wise et al, 1990)), and devices to support teleoperation. This previous, and still ongoing, research has provided much useful information for research and development on VE tactile interfaces. Developments from the teleoperation area have been particularly useful since the prime difference between teleoperation and VE tactile interfaces lies in what drives the tactile displays: tactile sensors in a remote environment or computer models. Much of the current research on tactile interfaces discussed in the literature is presented in the context of both teleoperation and VE application.

The remainder of this section discusses the work of individual research groups who are investigating tactile displays for use in VEs. In addition, two force feedback displays under development also provide tactile feedback; these are discussed in Section 6.2.3.1 and Section 6.2.3.2. Identified efforts for which information was not available include: work on the development of a tactile display glove at the Georgia Institute of Technology; work on tactile displays under Dr. Fearing at the University of California, Berkeley; and Dr. Canepa's investigation of piezoelectric and electrorheological materials for tactile displays at the Universita di Pisa, Italy.

6.1.3.1 Armstrong Laboratory

In the Armstrong Laboratory, Crew Systems Directorate, Human Sensory Feedback for Telepresence Project, researchers led by Capt. Chris Hasser have been looking at the use of tactile feedback for telerobotic and VE applications. In one study, these researchers conducted an evaluation of the perceptual characteristics of a 5 x 6 element array tactile stimulator, with elements spaced 3 mm apart in each direction. The actuators for this device were SMA wires, used to cause the tactile elements to rise and fall. In an experiment, three subjects were tested to see if they could perceived patterns presented with the device (Hasser and Weisenberger, 1993). Two sets of stimulus patterns were used. The first set consisted of eight static patterns built of one or two straight lines. The second set consisted of the same eight patterns, presented in successive frames to simulate movement across the finger. For an eight pattern set, chance identification is 12.5% correct. The subjects gave significantly higher scores for both sets of stimulus patterns. For the static patterns, correct identifications were made 90 to 100% of the time, and 80 to 100% of the time for the dynamic patterns. In both cases, varying stimulus frequencies gave little difference in performance. Together with a physical evaluation, this experiment demonstrated that SMA arrays have the potential for presenting complex information, such as that required to represent local object shape and surface texture. The tactile feedback array has been adapted for use in presenting a virtual tactile surface to the user. This device is called the HAPtic-TACtile (HAPTAC) and is itself being used in the TacGraph system to present data plots to blind persons. Since this early work, however, the researchers have become concerned that the bandwidth of present SMA arrays may be insufficient for many haptic exploration applications. They funded a Small Business Innovation Research project to improve SMA technology and found that higher bandwidth could only be achieved at the expense of more complex, heavier apparatus.)

In more recent work, the researchers have been investigating the integration of a single element tactile stimulator with the PHANToM force feedback system (see Section 6.2.2.9). With the PHANToM, the force feedback is delivered via a thimble into which the user inserts his finger (alternatively, the forces can be delivered via a stylus that is held by the user). The tactile stimulator was required to be capable of delivering both steady-state and vibratory forces. A key concern was to use a tactile actuator capable of adequate force with a mass low enough to avoid compromising the PHANToM's dynamic performance. In addition, to represent hard surfaces, the stiffness of the actuator system needed to be higher than that of the fingertip. The third requirement was to provide a bandwidth high enough for accurate representation of dynamic environments. After consideration of four actuator options (an electric motor with threaded screw reducer, SMA wires, pneumatic pistons, and solenoids), a solenoid actuator was selected for use. The resulting special tactile feedback thimble attaches to the PHANToM gimbal and is secured to the user's finger by means of velcro straps. Initial performance evaluation of the system found that an adaptive proportional-integral algorithm using continuously variable gain scheduling helped to compensate for nonlinearities in the solenoid actuator. The closed-loop behavior met the performance requirements of a maximum tactor force of 2 N and steady-state force accuracy of less than 0.12 N. The mass added to the force feedback system, however, degraded PHANToM's performance. Improvements in future prototypes are expected to reduce the mass of the tactile feedback hardware by over 30% (Hasser and Daniels, 1996).

Another effort with a force reflecting interface is looking at the application of Fitt's Law in VEs. For example, how scaling differences between finger movement and cursor movement impact a tapping task. Other factors, such as the addition of virtual masses to the fingertip, or viscous damping fields, may improve or degrade performance.

6.1.3.2 Begej Corporation

Begej Corporation is developing large-scale tactile displays under contract to NASA Johnson Space Center. The technology used in the tactile displays is expected to be patented and few details are currently available. What is known is that a large-area display, using 512 tactile elements, that can be worn over the upper torso, lower arms, and upper arms is being developed, together with a fingertip display using 37 tactile elements. The devices being developed may result in commercial products.

6.1.3.3 Harvard University

Dextrous manipulation for teleoperation is one of the research areas at Harvard University's Division of Applied Sciences and, for several years, researchers have been looking at tactile sensing and display devices to support such manipulation. One of the goals of this work is the development of a tactile shape display for use in the grasping surface of a force-reflecting master robot hand. Another is to determine the utility of vibration feedback and delineate the types of tasks where high frequency vibration information is important. Accordingly, these researchers, led by Dr. Robert Howe, have developed prototype tactile displays that deliver shape or vibration feedback and have conducted a series of studies using these displays.

The tactile shape display uses blunt (piano wire) pins driven by SMA actuators. Specification details for the display are given in Figure 69.

Specification	
Pin Tip	1.7 mm diameter
Pin Spacing	2.1 mm center-to-center
Rise Height	3 mm
Rise/Fall Time	62 msec
Pin Placement	4 layers of 6 pins
Pin controllability	Individually addressable
Force	1.2 N
Bandwidth	6 - 7 Hz, operates at 3dB
Display Dimensions	67 length x 26 width x 31 height (mm)

Figure 69. Prototype Tactile Shape Display (Harvard University)

In an informal study on the functionality of the tactile shape display, subjects initially were asked to classify patterns generated by the display as a point, line, or plane, and subsequently to distinguish between four different orientations of lines. All subjects correctly answered all tests providing initial confirmation that the display did generate recognizable spatial patterns (Kontarinins and Howe, 1995).

In order to investigate the role of shape information in telemanipulation, two shape displays were mounted on a master manipulator. This device was intended for use in precision pinch grasp operations, with the tactile displays providing shape information to the tips of the thumb and index finger, and the master manipulator providing contact forces. *(*The master manipulator was a two-fingered hand with 2 DOFs in each finger, controlled using a conventional bilateral force reflection control scheme. It operated with a force reflection bandwidth greater than 80 Hz, a rise time delay for the force feedback of 15 msec, and was capable of providing 0.7 N.*)* The remote slave manipulator used was a two-fingered hand very similar to the master manipulator, with tactile array sensors mounted on each robot fingertip to provide shape measurement. One study already completed using this system looked at subjects' ability to localize tactile features using the device (Kontarinins and Howe, 1995). The task chosen for this study was a simulation of tumor localization using palpation. The tumor was simulated by embedding a cylindrical 4 mm diameter piece of hard rubber beneath the surface of a block of foam rubber. For the experiment, a single row of the tactile array sensor and a single row (6 pins) of the tactile display were used. Subjects performed the task both with and without the tactile shape feedback. Force feedback was provided by the master manipulator in both conditions, but visual feedback was not provided. A total of 60 trials were performed by three subjects. When the tactile feedback was available, subjects located the tumor with an error ≤1 mm in more than 50% of the trials, and with an error ≤3 mm in more than 95% of the trials. When the shape information was not available, the mean absolute error was >13 mm.

Current work on tactile shape interfaces is following two directions. In one, the researchers are looking at ways to increase the bandwidth of the display to around 25 Hz. In the other, they are looking for inexpensive ways in which to manufacture such a device. Future work is expected to focus on identifying the tactile feedback bandwidth and dynamic range requirements needed for different tasks and developing a detailed specification for system performance. Additional work will include integrating the tactile feedback system with surgical instruments such as laparoscopic forceps.

With respect to their work with high frequency vibration feedback, the researchers have developed a prototype display that uses voice coil actuators assembled from miniature 0.2 watt loudspeakers. This prototype has a 3 mm range of motion, a peak inertial force of

0.25 N at 250 Hz, and physical dimensions of 67 x 26 x 31 (mm). As discussed by Kontarinis and Howe (1995), for the experiments outlined below two of the displays were mounted on the fingertips of the master manipulator described previously, and skin acceleration sensors were mounted on the slave manipulator to measure the vibrations to be produced by the tactile displays.

Experiments have been conducted that examined the utility of this type of display for three categories of tasks, that is, tasks where (1) the detection of vibration is the fundamental goal of the task, (2) vibrations indicate the state of the task, and (3) vibrations are not directly important to the task. For the first experiment, five subjects were asked to use touch inspection to distinguish a worn ball bearing set from a pair of such sets. Four feedback conditions were used: no haptic feedback, force feedback only, vibratory feedback only, and both vibratory and force feedback. Two protocols were used: in the first, subjects rotated both bearings in order to distinguish the worn set, and in the second they had to make the decision based on examination of only one bearing. Eighty trials were completed for the first protocol and 120 trials for the second. When the two set of bearings were available for examination, with no haptic feedback subjects made the correct selection in only 50% of the trials. Force feedback improved this result to 80% ($p \sim 0.1$), and with vibratory feedback the subjects achieved 100% success with or without force feedback ($p < 0.025$). When only one set of bearings was available for examination, with no haptic feedback the correct response rate was 53%, with force feedback only this rose to 73% ($p \sim 0.1$), and with vibratory feedback only the correct response rate was 66% ($p < 0.05$). With both types of haptic feedback, and the correct response rate rose to 90% ($p < 0.025$) (the researchers note that the subjects had difficulty in manipulating the bearing in the time provided without force feedback).

In second experiment subjects used the master manipulator to control the slave manipulator in piercing a 0.05 mm thick plastic membrane while minimizing the force used. For this task, a sharp needle was held between the fingers of the slave manipulator. The same feedback conditions were used as before, and three subjects performed a total of 152 trials. The force exerted during a trial was measured and used to determine subject reaction time and any excess force exerted. The results showed that the presence of either vibratory or force feedback significantly decreased mean reaction time by approximately one half that obtained when no haptic feedback was provided ($0.005 < p < 0.025$). The combination of vibratory and force feedback further reduced reaction time by approximately 50 msec.

In the final experiment, subjects were asked to perform a close-fit peg-in-hole assembly task as fast as possible. Here precise control of contact forces was the critical element and the task is an example of cases where vibrations are not directly important to the task. While the vibration feedback did not have any significant effect on task completion times, the researchers note that the subjects gave subjective reports indicating that the system felt more with "complete" when the vibration display was used.

Currently, the researchers are looking at medical applications for vibratory feedback, and mounting a tactile vibration interface system on such tools as catheters and biopsy needles. As a separate effort, commercialization opportunities for this technology are being investigated.

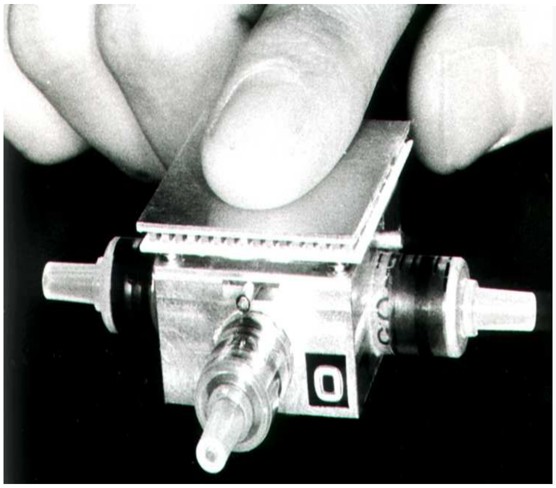
6.1.3.4 Hokkaido University, Japan

Led by Dr. Shuichi Ino, for the last several years researchers at Hokkaido University have been investigating the development of an integrated system of displays for providing sensory feedback to a human hand. A large part of this work has concerned the development of tactile displays for presenting shearing and pressure forces, and for presenting temperature feedback.

The researchers have experimentally examined the human capability for passive perception of shear, as reported in Section 6.1.1. The results of this experimentation yielded tactile display design requirements in the areas of strain generation mechanisms and temperature, and a test production device capable of generating 3-D micro displacement of shearing and pressure sensations has been developed. This device uses a pneumatic system to separate the display device from the driving mechanism, enabling a small and lightweight (22.5 g) display. The air pressure on each cylinder is computer-controlled using a electro-pneumatic regulator, controlling both the pressure and shearing sensations generated by means of a lateral-moving stage. The stage stroke is ±3 mm on both x and y axes. The maximum pressure output is 600 gf. Current work with the display is focusing on the development of a device suitable for mounting on a fingertip and further evaluation of its psychophysical characteristics.

With respect to temperature feedback, the researchers have conducted experiments that investigated human ability to recognize different materials (aluminum, glass, rubber, polyacrylate, and wood) based on differences in fingertip skin temperature when touching the material (Ino, 1993). The distinguishing factor was found to be temporal temperature difference. Using this information, a tactile temperature display was developed. The temperature of the display surface is measured by a thermocouple and a Peltier module allows the display to act as both a heater and cooler. A photograph and further details for this display are given in Figure 70.

Using this device, and the temperature change patterns acquired in the psychophysical experiments, an experiment was conducted to assess the effectiveness of the display in allowing users to distinguish between objects based on temperature feedback. In this experiment, artificial thermal stimuli were presented to four subjects who were asked to identify the material. Analysis of the results showed no significant difference between identifications made using the real materials and the temperature display. However, neither form of identification was completely correct in every case, and the researchers suggest that the presentation of temperature information be used as just one element of tactile feedback systems intended to support absolute material recognition.



Specification	
Temperature Range	-10 to 60° C
Temperature Resolution	0.1° C
Display Dimension	16 sq cm
Display Weight	30 g
Interface	RS-232

Figure 70. Temperature Display (Hokkaido University)

6.1.3.5 Hull University, UK

Researchers at Hull University, Department of Electrical Engineering, are looking at the use of electrorheological fluids for tactile displays. The fluids under consideration are primarily a colloidal dispersion consisting of an insulative base oil and a slightly conductive dielectric solid particulate. Under the stimulus of an electric field, these fluids have the ability to change from a liquid to a pseudo-solid state almost instantaneously and their malleability is dependent on the strength of the electric field. One of the advantages of this type of display is the absence of moving parts, if only the display of contact and shape information is required. The presentation of surface textures would require a system of control electronics.

The researchers, headed by Dr. Taylor, have developed a single cell display and are now working to develop a second generation display that will employ an array of electrorheological elements. This display is expected to be ready to embed in a VE tactile interface device within the next year.

6.1.3.6 Massachusetts Institute of Technology

At the Massachusetts Institute of Technology (MIT), Department of Mechanical Engineering, researchers in the Touch Laboratory are looking at human haptics and its relationship to machine haptics. This work is being led by Dr. Mandayam Srinivasan. The overall goals are to (1) develop an understanding of the human as the perceiver of, and the operator on, the environment; and (2) to apply this basic knowledge in the areas of rehabilitation, robotics, and human-machine interfaces for VEs and teleoperation. In particular, current work is focusing on haptic information acquisition and the control of contact tasks with the hand, with an emphasis on the associated information processing mechanisms. It includes investigation of the biomechanics, neurophysiology, and psychophysics of touch, and the development of a computational theory of haptics. Collaborators in much of the work include Dr. Nat Durlach and Dr. Ken Salisbury from MIT, and Dr. Robert LaMotte from the Yale University School of Medicine.

As part of a project focused on haptic interface development for VEs, Dr. Srinivasan's group has developed two major devices for performing psychophysical experiments, the Linear and Planar Graspers. These are in use, along with the PHANToM (see Section 6.2.2.9). Software to allow the haptic devices to present simulations of fundamental mechanical object properties, such as compliance, viscosity, and mass; to display shape, texture, and friction of solid objects; and to portray virtual walls and corners has been developed. Initial psychophysical experiments have measured the manual resolution of stiffness, viscosity and mass, investigated the influence of visual information on haptic perceptions of stiffness, and looked at the feasibility of various haptic display algorithms for presenting the shape, texture, and friction of solid surfaces. These experiments have yielded insights that show how human sensory perceptions can be used to promote haptic sensations in the user. For example, one finding is that the perception of the stiffness of objects like virtual push-buttons can be significantly altered by presenting visually skewed positional information to the subject. Additional psychophysical experiments are underway, aimed at characterizing the effectiveness of refined, computationally-efficient simulations and rendering algorithms in conveying desired object properties to the human user.

Recently, a haptic rendering technique called "force shading" (analogous to "Phong shading" in graphics) has been demonstrated to give users the feel of smoothly curved surfaces, even when the surfaces are represented as polyhedrons. In investigating multimodal displays, the effect of contact sounds on the perception of object rigidity is being explored.

The development of hardware and software haptic interfaces for human interactions with multimodal VEs will be continued in future work. This work is expected to include the development of high performance tactile sensors and displays, as well as a variety of haptic rendering algorithms that take advantage of human illusions in perceiving multimodal sensory inputs.

6.1.3.7 Research Center at Karlsruhe, Germany

Researchers at Karlsruhe Research Center, Department of Engineering Technology, are developing a tactile feedback system for use with flexible endoscopic forceps. These researchers, led by Dr. Harald Fischer, have developed a tactile display that consists of three 24-needle printing heads thus providing a total of 72 actuators, although only 64 are actually used. Individual needles are electromagnetically triggered by opto-decoupled printout boards and vibrate at a maximum frequency of 600 Hz to present contact pressure sensations. The tactile display is mounted on a box. It is driven to respond to operator applied forces detected by a force-movement sensor placed in the distal shaft of the forceps, grasping forces applied to the tissue that are detected by a miniature pressure transducer, as well as pressure distribution between tong and tissue as measured by a tactile sensor placed between the jaws of the forceps. In this way, the distribution of pressures and handling forces are sensed and displayed to the fingertip of the surgeon, they are also displayed graphically on a PC screen and sent to a plotter. A technical specification of this device is not publicly available at this time.

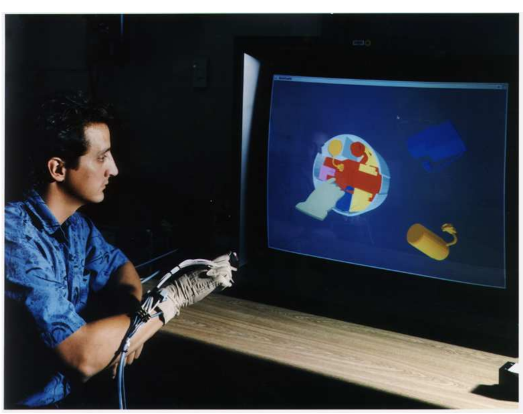
Future research on the tactile interface system will focus on the development of an analog linear device with 64 needles that will be mounted directly at the end of the laparoscopic forceps so that the surgeon can operate the system with a single finger. An optical sensor array for the distal end of the forceps will also be developed.

6.1.3.8 Sandia National Laboratories

Dr. Dave Andaleon at Sandia National Laboratories, is leading researchers in developing fingertip tactile feedback devices for VE applications. Specifically, the goal of this work is the development of a high density tactile array compatible with standard VE device interfaces.

After a review of haptic feedback research and products, the researchers developed a set of quantitative and qualitative evaluation metrics and a tactile feedback testbed for evaluating tactile stimulus technologies (hydraulic/pneumatic, electro-magnetic, piezoelectric, and bi-metallics such as shape memory alloys, polymeric gels, electrorheological, and magnetostrictive materials). On the basis of these evaluations, it was decided to build a electromagnetic actuator. (A patent for the actuator design is pending.) This actuator operates in the frequency range 8 - 100 Hz, it is capable of 762 micron indentation and exerting a maximum pressure of 1.2 N/cm^2.

For the tactile display itself, a 2 x 3 array of actuators is mounted on a pad, and pads are attached to a user's fingers using velcro straps. The software developed to support the tactile interface system allows tactile displays to be used on the thumb, index finger, middle finger, and palm simultaneously. Each actuator in a tactile display is individually controlled with respect to magnitude, frequency, and phase. A serial RS-232 interface is provided through a host computer with analog output boards. A performance specification for the tactile display, and a photograph, are given in Figure 71.



Specification	
Update Rate	50 Hz
Operating Modes	Impulsive, vibratory
Actuator Placement	2 x 3 array
Actuator Spacing	0.288 in
Actuator Controllability	Individually controllable
Max. Pressure	1.2 N/cm^2
Latency	20 in
Bandwidth	8 - 100 Hz
Display Weight	20 g

Figure 71. Tactile Display (Sandia National Laboratories)

Initial tests with the tactile interface system included the simple mapping of material texture to actuator frequency and modeling cubes as solids using object collision detection. The stimulus types investigated were magnitude, frequency and phase, spatial and temporal frequency, and spatial and temporal patterns.

Current work is focusing on developing software that uses the tactile display to present a variety of textures and other surface information. The resulting tactile interface system will be integrated into a situational training VE that supports multiple participants. Insights gained from this use of the tactile interface system will be used in further investigation of actuator performance and actuator ruggedness. Future work also is expected to look at the value of providing tactile feedback in the absence of any kinesthetic feedback.

6.1.3.9 TiNi Alloy Company

Under contract with the Human Systems Center at Brooks Air Force Base, TiNi Alloy has developed a tactile display consisting of a 5 x 6 array of tactor pins. A photograph and details for this display are given in Figure 72. The display is supported by microcontroller hardware and software to constitute a complete tactile system.

An initial informal study of the effectiveness of the tactile display has been performed. In this study, when the tactile display was mounted on a digitizing puck, so that the user's fingertip rested on the tactile display while his hand moved the puck across a flat surface, subjects were able to correlate patterns shown on a screen and those presented via the pins. In a more formal, but preliminary evaluation, three subjects were able to identify a set of static patterns and a set of moving patterns (Hasser and Wesenberger, 1993). Currently, the display is being refined to support its efficient manufacturing. As part of the same contract effort, TiNi Alloy's engineers are augmenting the force feedback provided by the PHANToM with tactile feedback; this is expected to be achieved by mounting a single tactor in the PHANToM thimble and activating this tactor remotely, perhaps using pneumatic actuators.

Specification	
Pin Tip	1 mm diameter
Pin Spacing	1.5 mm
Rise Height	1 mm
Rise/Fall Time	100 msec
Pin Placement	5 x 6 array
Pin Controllability	Individually controllable, binary positions
Force	6 g
Bandwidth	2 - 3 strokes/sec
Display Dimensions	14 x 8 x 4 cm
Display Weight	16 oz

Photo courtesy of TiNi Alloy Company

Figure 72. Programmable Tactile Array (TiNi Alloy)

In an effort funded by the Naval Sea Systems Command, TiNi Alloy is further investigating the use of its SMA thin film pneumatic micro-actuators for actuating tactile feedback. The intended application of this work is a tactile display that can be positioned on a pilot's torso and used to alert him to special circumstances.

6.1.3.10 University of Salford, UK

A glove with tactile, contact pressure, and temperature feedback, referred to as tele-taction, is being developed by researchers at the University of Salford, Department of Electronic Engineering.

A tactile sensation of texture and slip is provided for object identification and grasp stability control using vibrational stimulation from a piezo-electric actuator. The feedback module is a PZT (lead zirconate titanate) ceramic disc, 10 mm in diameter and 1 mm thick, that is mounted on a metal disc 15 mm in diameter and 1 mm thick. This transducer is enclosed in a PVC film and driven by a high voltage (up to 350 V). The total unit weight is around 2 g. Finger positions are sensed using Hall Effect sensors that provide measurement of the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) finger joints. These various devices are mounted on a glove to provide feedback to a single finger. Contact forces, or pressure, are provided by pneumatic bladders that are operated by an independent pneumatic powerpack, connected to the glove via valves and piping. This feedback is transmitted to thirty locations on the anterior surfaces of the fingers and palm of a hand. In tests of the texture feedback, subjects were able to distinguish between ribbon cable, writing paper, tissue paper, a small file, cloth, and four different textured steel plate surfaces. They also were able to detect slips of 0.5 mm or more. In the case of pressure feedback, the subjects were able to distinguish between four different force levels (2, 10, 30, and 60 N).

Thermal feedback using a Peltier Effect Heat Pump supports object or material identification and, also, safety. A rapid response thermal-couple is mounted on the Peltier unit, in contact with the user's skin, allowing tracking of the user's skin temperature and the provision of a rate of cooling or heating relative to this temperature. A small aluminum plate is attached to the exterior surface of the heat pump to act as a thermal regulator that minimizes the temperature gradient and a small heat sink with an integral fan unit permits high cycle rate responses. This thermal device is set to generate temperatures in the -5 to 50°C range, with rate changes of up to 20°/sec. With thermal feedback, subjects were able to distinguish between five objects with different temperatures or thermal conductivities (ice cube, a soldering iron, insulating foam, aluminum block, and room condition). Finally, temperature was used as a substitute for pain or danger feedback by rapidly increasing the temperature to 50° C; in tests, subjects were able to respond to this feedback with a reaction time of 0.9 sec. The feedback unit weighs 10 g, measures 15 x 15 x 3 mm and operates at 10 W.

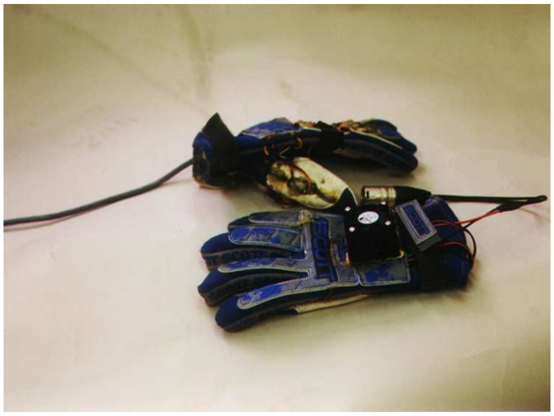


Figure 73. Tactile Feedback Glove (University of Salford)

The primary aim of this work is in the development of an effective interface for telepresence control of highly dextrous robotic units. The objective is to produce a robot that will respond to natural human inputs and feedback video, audio, and tactile data that is readily comparable with 'normal' human experience. The feedback glove, shown in the foreground of Figure 73, itself is part of an input and feedback system that includes 7 DOF exoskeleton arms used to control a twin-armed robot. The robot arms will be mounted with dextrous manipulators that include sensors for the detection, at a minimum, of pressure, vibration, and temperature and so provide data on such features as object shape, profile, and hardness. The sensors need not be limited to normal human sensations and may be used to provide information on characteristics such as conductivity and radioactivity, encoded as tactile feedback.

With respect to VEs, the researchers' objective is to create an effective feel for virtual objects ranging from switches and levers to walls. They plan to use the sensor inputs acquired from robot contact with real objects to program corresponding features for use in VEs.