6.2 Kinesthetic Interfaces

Since the majority of a human's interaction with his environment consists of manipulating objects, this capability is a prerequisite for many practically useful VEs. Manipulation can be achieved via indirect means such as voice, keyboard, or mouse commands. A natural form of manual manipulation, however, requires use of the types of interaction devices discussed in Section 5, augmented with force feedback to simulate object properties such as overall shape, stiffness, and weight. The importance of force feedback has been well established in the teleoperation community (see, for example, (Hill and Salisbury, 1976), (Hannaford, 1989), and (Howe, 1992)). There have also been some experiments that have investigated the value of force feedback for VEs. In a molecular docking VE, Ouh-Young, Beard, and Brooks (1989) demonstrated how a visual interface supported by force feedback gave significantly better performance than the visual display alone and, when only a single type of display was available, force feedback gave a better task performance than the visual display. More recently, it has been shown that force feedback for simple grasping tasks can reduce task error rate and learning time by over 50% (Gomez, Burdea, and Langrana, 1995).

Essentially, there are three components to providing a force feedback interface for VEs: measurement of the movement of the user's fingers, hand, and/or arm, and sensing any forces he exerts; calculation of the effect of the exerted forces on objects in the VE and the resultant forces that should act on the user; and presentation of these resultant forces to the user's fingers, wrist, and arm as appropriate.

Force feedback devices are either earth-grounded, off-the-body devices or exoskeleton devices worn by the user that, themselves, are either anchored to the ground or a body part closer to the point of force application. Hasser (1995) discusses this basic difference and also provides a discussion of the different types of actuators and transmission methods used for force feedback devices. A summary of the some of the actuator technologies, taken from Hasser's report, is provided in Table Table 11. Of these technologies, electromagnetic motors, hydraulics, and pneumatics are technologies in current use. Piezoelectric and magnetorestrictive technologies are still the subject of research and development.

There are some commercial VE systems that have limited force feedback capability. Currently, these are all entertainment systems where the user "operates" some vehicle and forces are presented to the user via some control device such as a steering wheel. Within the next several months, however, some surgical training systems that provide force feedback via surgical instruments are expected to come to market. The best example of a non-commercial VE system in practical use that employs force feedback is the molecular docking system at the University of North Carolina, see Section 6.2.3.12 below.

6.2.1 The Human Kinesthetic Sense

As discussed by Boff, Kaufman, and Thomas (1978), kinesthesia provides humans with an awareness of the position and movement of body parts, whether such movement is self generated or externally imposed. The receptors that support this sense are found in skin, joints, and muscles. The relevant skin receptors provide information about skin stretch and cutaneous deformation and were discussed previously. Joints contain two types of receptors: Golgi endings found in joint ligaments, and Ruffini type endings found in joint capsules. These receptors respond to joint torque and capsule stretch, respectively. They are slowly adapting and thought to signal extremities of joint flexion and extension. Muscles also contain two types of receptors, Golgi tendon organs that monitor muscle tension, and muscle spindle organs that measure muscle stretch and its rate of change.

Together, these various receptors provide information about joint angles, muscle length and tension, and their rates of change. However, the most important receptors for kinesthesia seem to be the muscle spindle organs. These receptors are thought to be the primary candidate for static position detection and, probably with skin receptors, they provide a sense of movement. But none of the skin, joint, or muscle receptors provide awareness of weight or effort; instead, this sense seems to arise mainly from signals derived entirely within the central nervous system.

It is important to note the asymmetric nature of the human somatosensory system, that is, the fact that the force control and perceptual bandwidths of the human differ. For example, Brooks (1990) reports that the maximum frequency with which a typical hand can

Table 11. Force Feedback Actuator Technologies[a]

Technology	Description	Advantages	Disadvantages
Electromagnetic Motors	Electromagnetic motors produce torque with two time-varying magnetic fields, caused by two coils or a coil and a magnet	- Easy to control - Clean, quiet - Easy design and installation	- Heavy components - Low power densities at small scales - Heat dissipation problems - Low static force capability
Hydraulics	A hydraulic fluid is pressurized by a power plant, controlled by servo-valves and delivered to rotary or linear actuators through pressurized fluid lines	- Force capability, power output, stiffness, and bandwidth unmatched by other technologies	- High mass - Tendency for fluid leaks - Design difficulty - Expensive
Pneumatics	A gas (normally air) is pressurized by a power plant, controlled by servo-valves, and delivered to rotary or linear actuators through pressurized fluid (air) lines	- Good static force capability - Lighter than hydraulics - Pneumatic power plants and distribution systems easier to manage than hydraulics	- Relatively low bandwidth - Low actuation stiffness - Low power capability
Piezoelectric	Piezoelectric motors translate the vibration of piezoelectric materials to linear or rotary motion using frictional forces to produce usable torques or forces at low speeds, without the need for gear reduction.	- High forces at low speeds in small package	- Requires precision machining - Necessary power gating can cause annoying and potentially hazardous noise, depending on the design
Magnetorestrictive	Magnetorestrictive materials change shape when subjected to magnetic fields. Magnetorestrictive motors also mechanically rectify small oscillatory motions of the driving element(s).	- High forces at low speeds in small package	- Necessary power gating can cause annoying and potentially hazardous noise, depending on the design - Heat dissipation can be a problem - Requires precision machining
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 - Limited bandwidth

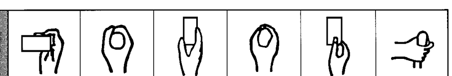
a. Based on Hasser (1995, 1996)

transmit motion commands to a hand master is 5 - 10 Hz, while the upper bound for receiving position and force signals is not less than 20 - 30 Hz.

Researchers at various research laboratories and departments at MIT are collaborating in experiments to collect human factors data (Tan et al, 1994). This data will be used to develop a detailed catalog of human factors data that aids better design and evaluation of haptic interfaces. These researchers report that the JND for force sensing is around 7%, regardless of reference force or body site. The force required for a human to perceive an object as rigid ranges from 153 to 415 N/cm. The maximum controllable force ranges from 16.5 to 192.3 N, increasing from the most distal finger joint to the shoulder joint (here there are significant gender differences). Force output resolution is about 0.36 N regardless of body site, while, in terms of percentages, the resolution tends to decrease from the PIP finger joint to the shoulder joint. The JND for pressure perception is roughly 0.06 - 0.09 N/cm, regardless of contact position. The greater the contact area, the more sensitive the human arm is to pressure; the JND decreases by a factor of roughly four (from 15.6% to 3.7%) when the contact area increases by a factor of sixteen (from 0.2 in^2 to 3.14 in^2).

On the whole, these figures are consistent with the findings of other researchers. For example, Shimoga (1993a) reports that the human fingers can sense force variations of 0.5 N; if this load is distributed, the pressure must not be below 0.2 N/cm^2 which is the minimum pressure that a human finger can sense. In summarizing much available data, Shimoga also states that human fingers can exert 30 - 50 N for brief periods, and 4 - 7 N for sustained periods. Massie and Salisbury (1994) have found that, in practice, a virtual surface with a stiffness of at least 20 N/cm is perceived as a solid and immovable wall by users.

Table 12. Variability of Forces Exerted in Human Grasping



5% Female	53 lbs	53 lbs	7.5 lbs[71]	7.5 lbs	9 lbs	4 lbs[73]
95% Male	147 lbs	147 lbs	30 lbs[71]	30 lbs	32 lbs	13 lbs[71]
Torque Capability	Excellent	Excellent	Good	Poor	Some	Excellent
Endurance @25% Load	Good	Good	Poor	Fair	Fair	Good

7. Data unavailable; 1. Values assumed to about the same as pincher grasp but supporting evidence not available; 2. Mean value 100 male subjects; 3. Value assumed to be 1/3 of male value.

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Jacobus et al (1992) have summarized the variability of force output in different types of grasp as shown in Table 12. As indicated in this table, humans use several different types of hand grasp in manipulating objects, and the functional characteristics of these grasps differ. Since the current technology uses differ methods for providing force feedback depending on the type of grasp used, it is useful to briefly delineate these different types. Schlesinger (1919) first categorized grasps as cylindrical, fingertip, hook, palmar, spherical, and lateral. Since the type of grasp used tends to reflect the task to be performed, Napier (1956) suggested a categorization based on the distinction between power grasps and precision grasps. Additional schemes have been based on the concept of virtual fingers, oppositions provided by various hand configurations, and in terms of prehensile and non-prehensile grasps. Cutkosky and Howe (1990) provide a grasp taxonomy that relates these different categorization schemes, as shown in Figure 64. They also define grasp attributes as dexterity, precision, sensitivity, stability, and security.

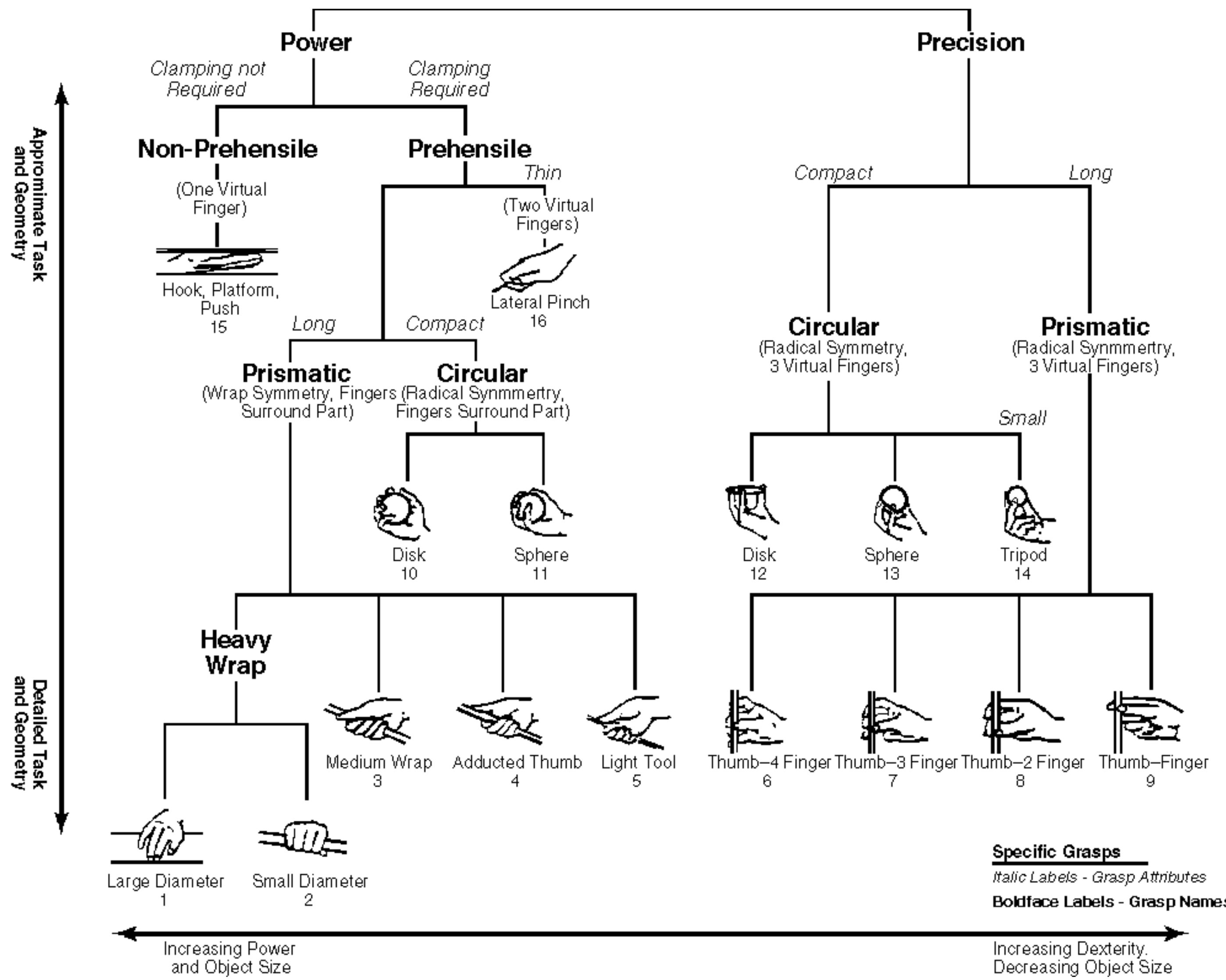


Figure 64. Taxonomy of Manufacturing Grasps

Reprinted by permission of the Robotics Institute, Carnegie-Mellon University.

Grasping does not rely only on kinesthetic sensing, tactile signals play a significant role in almost all manipulative tasks. Johannson (1991) argues that cutaneous surface deformations directly reflect the accomplishments of many manipulative actions, and may serve as preconditions for triggering some of the motor commands associated with these actions; tactile signals also provide information about an object's physical properties that are used in guiding the use of manipulative forces.

Experiments conducted in a teleoperator environment provide some data on operator fatigue and discomfort that might arise using hand force feedback interfaces in a VE, and that can reduce an operator's ability to estimate force magnitudes and variations (Wiker, 1989). The factors that aggravate fatigue and discomfort are cited as grasping force and work-to-rest ratio. Operator comfort will be within safe levels if the grasping, or reflected, forces are less than about 15% of the maximum exertable force, that is, the index, middle and the ring fingers can safely exert about 7, 6, and 4.5 N, respectively, without encountered fatigue and discomfort.

6.2.2 Commercially Available Devices

This discussion is limited to force feedback devices that are specifically intended for use in VEs. Even so, recent years have seen several devices, of quite different types and capabilities, come to market. The features of these devices are summarized in Table 13. Information on another commercial product, Sarcos Inc.'s Hand Master, was not available.

In addition to these existing products, Virtual Technologies, Inc. is currently developing its *Cyber*Force product that will augment the *Cyber*Glove with force feedback. This new force feedback device will provide restrictive forces to the user's fingertips and is expected to be released in Summer '96.

6.2.2.1 4 DOF Force Feedback Master (Surgical Simulator)

Initially designed for use in medical simulations, the EXOS, Inc. 4 DOF Force Feedback Master provides force feedback to the hand and arm in 4 DOFs. Feedback is provided via a handle connected to a larger tool shaft, which is pivoted at one point with an active 3 DOF gimbal. The fourth DOF is provided by a linear sliding module, allowing the tool to be translated ("heaved") along the shaft of the tool. One possible application of the device is the simulation of minimally invasive surgery, in which forces encountered by touching virtual tissue and organs with a laparoscopic tool are simulated and displayed to the user at the handle. The additional information available for this device is given in Figure 65. The 4 DOF Force Feedback Master is made to order and pricing information is not available.

6.2.2.2 Force Exoskeleton ArmMaster

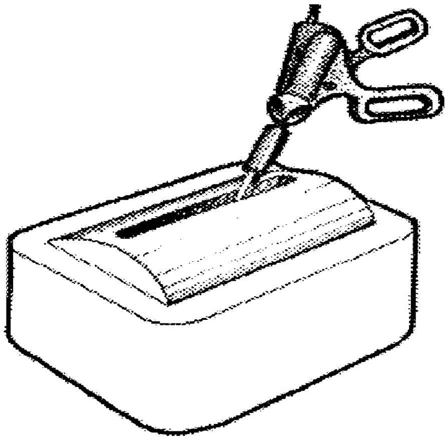
Structured as an exoskeleton, the EXOS, Inc. Exoskeleton Force ArmMaster (EAM II) has 5 active DOFs and additional passive freedoms designed for comfort and the ability to adjust to different arm sizes. An active gimbal structure suspended above the

Table 13. Characteristics of Commercially Available Force Feedback Devices

Device Name	Vendor	Device Type	Forces Provided To	Active DOFs	Force Resolution	Applied Force[a]	Price
4 DOF Force Feedback Master	EXOS, Inc.	Desktop	Hand via joystick	4	Unavailable	Range 5.1 - 12.0 oz-in (cont), range 20-59 oz-in (peak)	Contact vendor
Force Exoskeleton ArmMaster	EXOS, Inc.	Exoskeleton	Shoulder and elbow	5	Unavailable	Range 3.4 - 56.6 in-lb (cont), range 29.0-489.0 in-lb (peak)	Contact vendor
Impulse Engine 3000	Immersion Corporation	Desktop	Hand via joystick	3	0.00435 N	8.9 N (cont)	$7,950
Laparoscopic Impulse Engine	Immersion Corporation	Desktop	Hand via tool handle	5	0.00435 N	8.9 N (cont)	$8,950
Interactor	Aura Systems, Inc.	Vest	Torso via vest	N/A	N/A	N/A	$99
Interactor Cushion	Aura Systems, Inc.	Cushion	Back via cushion	N/A	N/A	N/A	$99
HapticMaster	Nissho Electronics Corporation	Desktop	Hand via knob	6	2.85 gf	1.2 kgf, 5.6 kgf/cm (cont), 1.8 kgf (peak)	Unavailable
Hand Exoskeleton Haptic Display (HEHD)	EXOS, Inc.	Exoskeleton	Thumb & index finger joints, palm[b]	4	Unavailable	Range 1 - 5 lb (peak)	Contact vendor
PER-Force 3DOF	Cybernet Systems Corporation	Desktop	Hand via joystick	3	0.035 oz	1 lb (cont), 9 lb (peak)	$9,950
PER-Force Handcontroller	Cybernet Systems Corporation	Desktop	Hand via joystick	6	12 bit	2- 3 oz (min), 20 - 25 lb (peak)	Contact vendor
PHANToM	SensAble Devices, Inc.	Desktop	Fingertip via thimble	3	12 bit	1.5 N (cont), 10 N (peak)	$24,000
SAFiRE	EXOS, Inc.	Exoskeleton	Wrist, thumb & index finger	8	Unavailable	Range 1 - 2 lb (peak), wrist 2 lb (peak)	Contact vendor

a. Some figures are for torque, not force

b. Includes tactile display presenting a sense of slip to the thumb and index finger.



Specification

		Cont.	Peak
Force/Torque	Pitch/yaw	12 oz.-in	59 oz-in
	Roll	5.1 oz-in	20 oz-in
	Heave	7.5 oz	25.3 oz
Resolution	Pitch/yaw	0.1°	
	Roll	0.1°	
	Heave	0.001 in	
Range of Motion	Pitch/yaw	140°	
	Roll	350°	
	Heave	4 in	
Device Size	12L x 13W x 7H (in)		
Device Weight	~6 lb		
Interface	Serial, custom		

Photo courtesy of EXOS, Inc.

Figure 65. 4 DOF Force Feedback Master

shoulder provides 3 DOF force feedback to the upper arm. A remote center mechanism provides 2 DOF force feedback to the lower arm. The active DOFs on the shoulder use DC motors with a closed loop cooling system that allows the motors to produce twice the usual torque without overheating. The EAM II is mounted to the arm via an air bladder that accommodates small misalignments of the device. The system is completely back-mounted and designed to be lightweight and portable. If desired, position sensing, using optical encoders, provides motion commands to the simulation or slave. A photograph of the EAM II and further details are given in Figure 66.

Specification

		Cont.	Peak
Torque	Shoulder Ab/Ad, F/E	56.6 in. lb.	489.0 in. lb.
	Shoulder I/E	20.3 in. lb.	175.0 in. lb.
	Elbow F/E	14.0 in. lb.	121.0 in. lb.
	Forearm S/P	3.4 in. lb.	29.0 in. lb.
Powered DOF	Shoulder	3	
	Elbow	1	
	Forearm S/P	1	
Joint Motions	Shoulder Flexion/Extension		120°
	Shoulder Ab/Adduction		120°
	Shoulder Int/External Rotation		100°
	Elbow Flexion/Extension		100°
	Forearm Supination/Pronation		100°
Backlash	<2 °		
Friction	Approx. 4% of torque		
Size	Adjusts to fit most male, female arms		
Weight	~4 lbs. on arm		
	~18 lbs. back mounted (single arm)		
	~20 lbs. back mounted (double arms)		

Photo courtesy of EXOS, Inc.

Figure 66. Force Exoskeleton ArmMaster

The Force ArmMaster can be configured for one or two arm operation, or integrated with SAFiRE or HEHD to provide force feedback to the wrist and fingers. The Force ArmMaster is made to order and pricing information is not available.

6.2.2.3 Impulse Engine Family

Based on its Impulse Engine, Immersion Corporation markets a range of tool-based force feedback devices. All Impulse Engine products use servo-motor actuators. They come with device drivers for a variety of machines ranging from PCs and Macs, to Silicon Graphics platforms. A small number of demonstration programs also are available. The Impulse Engine 3000 is a 3 DOF pen-based device priced at $7,995; a photograph and specification details are given in Figure 67.

Specification	
Continuous Force	8.9 N
Force Resolution	0.00435 N
Position Resolution	0.01 mm
Backdrive Friction	<0.14 N
Bandwidth	650 Hz
Workspace	13 cm (linear)

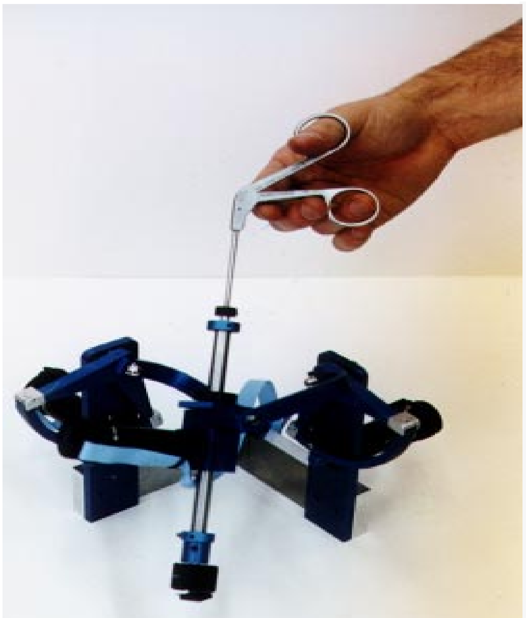
Photo courtesy of Immersion Corporation

Figure 67. Impulse Engine 3000

The Laparoscopic Impulse Engine is an interface device specifically designed for virtual simulations of laparoscopic and endoscopic surgical procedures. This device can be fitted with a selection of instrumented surgical tools, or tool handles. The surgical tool can pivot (with 2 DOF) around the insertion point with an approximate range of 100° and a maximum torque of 60 oz/in. A third DOF allows for translation in-and-out along the insertion axis with a maximum travel of 4 in, and forces of up to 2 lbs. The fourth DOF allows the instrument to spin a full 360° along its longitudinal axis, and the fifth DOF provides for the open-close motion of the instrument grip. Position sensing is provided for all 5 DOFs, and force feedback for the tool pivoting and travel along the insertion axis. This device is priced at $8,950, or $15,950 for a pair of devices. A photograph and specification details for the Laparoscopic Impulse Engine are given in Figure 68.

Another tool-based force feedback device marketed by Immersion Corporation is the Needle Insertion Simulator. This device is intended for use in a training system that tracks the insertion of a virtual needle while providing force feedback that simulates the needle's penetration through various layers of tissue. It is composed of a single linear axis with a travel of 13 cm, and provides forces up to 8.9 N. A final tool-based device is the Virtual Catheter Interface.

Immersion Corporation is continuing refinement of its current products to develop higher performance versions. A future area of research is expected to be the development



Specification

Continuous Force	8.9 N
Force Resolution	0.00435 N
Position Resolution	0.01 mm
Backdrive Friction	<0.14 N
Bandwidth	650 Hz
Workspace	13 cm (linear)

Photo courtesy of Immersion Corporation

Figure 68. Laparoscopic Impulse Engine

of virtual fixtures, that is, abstract perceptual information that can be overlaid on a virtual workspace to aid in task performance.

6.2.2.4 Interactor and Interactor Cushion

The Interactor products from Aura Systems, Inc. are very different from the other force-feedback products discussed here: they monitor an audio signal and use Aura's patented electromagnetic actuator technology to convert bass sound waves into vibrations that can represent such actions as a punch or kick. Both the Interactor vest and the Interactor Cushion plug into the audio output of a stereo, TV, or VCR. The user is provided with controls that allow adjusting the intensity of vibration and filtering out of high frequency sounds. The audio signal itself is reproduced through a speaker embedded in the vest or cushion.

The Interactor Vest is worn over the upper torso and costs $99, further details are given in Figure 69. The Interactor Cushion is placed against a seat back and the user leans against it, its price is $99. Further details for the Interactor Cushion are given in Figure 70.

6.2.2.5 HapticMaster

The HapticMaster was developed by Dr. Hiroo Iwata at the University of Tsukuba, Japan, and is now marketed by Nissho Electronics Corporation. This device is a desktop instrument that provides 3-D force and 3-D torque to the user via a knob grasped by the user's fingers. The actuators are three sets of pantograph linkages, each driven by three electric motors. The top of each pantograph is connected to a vertex of a small platform by

Specification

Frequency Range	0 - 100 Hz
Dimensions	~19 H x 13 W x 4.5 D in
Weight	8.5 lb

Photo courtesy of Aura Systems, Inc.

Figure 69. Interactor

Specification

Frequency Range	0 - 100 Hz
Dimensions	~17 L x 13 W x 4.5 D in
Weight	4 lb

Photo courtesy of Aura Systems, Inc.

Figure 70. Interactor Cushion

a spherical joint, and the knob is mounted in the center of this platform. A specification for the HapticMaster and a photograph of the device are given in Figure 71.

Software that computes positions and forces is available for the PC. The Haptic-Master itself is controlled by an interface unit that provides signal amplification and A/D converters for measuring master angles.

6.2.2.6 Hand Exoskeleton Haptic Display

The EXOS, Inc. Hand Exoskeleton Haptic Display (HEHD) is an integrated multi-modal haptic display system that provides force feedback as well as a sense of slip to the thumb and index finger. The device consists of a hand exoskeleton (a modified SAFiRE, see Section 6.2.2.10) providing 1 DOF force feedback to the thumb and 2 DOF force feed-

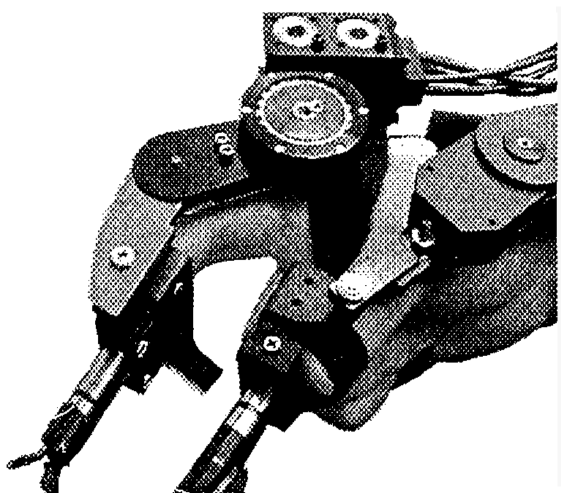
Specification	
Peak Force	1.8 kgf
Continuous Force	1.2 kgf
Continuous Torque	5.6 kgf/cm
Force Resolution	2.85 gf
Position Resolution	0.4 mm
Backdrive Friction	0.1 kgf
Max. Payload	2.5 kg
Update rate	90 Hz
Workspace	Sphere 40 cm diameter
Interface	RS-232

Photo courtesy of Nissho Electronic Corporation

Figure 71. HapticMaster

back to the index finger. The slip displays each provide a sense of slip in one direction and are integrated into the exoskeleton. The exoskeleton can be mounted to a boom that provides 2 DOF position sensing in a vertical plane as well as force feedback in the vertical direction. When fully integrated, the system can be used for virtual pick-and-place tasks in which weight, contact, and slip information is passed by force and slip feedback.

The software that controls the HEHD is available for 386 or higher IBM-compatible PCs and the Silicon Graphics Indigo2. A photograph and specification details are given in Figure 72. Like all EXOS, Inc. force feedback products, the HEHD is built to order and general price information is not available.



Specification		
Maximum Force	Slip display	1 lb
	Horiz. force reflection (thumb)	1 lb
	Horiz. force reflection (index)	1 lb
	Vertical force reflection	5 lb
DOF	Powered: Force	4
		2
	Slip	2
	Passive	
Range of Motion	Thumb	120 °
	Index finger MCP joint	120 °
	Index finger PIP joint	90 °
	Vertical range of motion	7 in.
Size	Adjustable to fit most hands	
Interface	VMEbus	

Photo courtesy of EXOS, Inc.

Figure 72. Hand Exoskeleton Haptic Display (HEHD)

6.2.2.7 PER-Force 3DOF

Cybernet Systems Corporation markets a 3-D force-feedback, backdrivable joystick called PER-Force 3DOF. This device is primarily intended for use in VE and teleoperation applications. The user can move the joystick handle in three revolute directions and these are mapped to movements in terms of *x*, *y*, and *z* axes or angular movements in the VE. Unlike many force-feedback devices, PER-Force can be operated in different control modes. That is, the computer can read either the joystick joint or the transformed position, velocity, or force. Similarly, via small, brushless DC servo motors on each of the revolute axes, force-feedback can be presented to the user in terms of position, rate, or force. Three cueing buttons, an analog trigger, and a palm-actuated deadman safety switch are mounted on the handle; these controls are all programmable and can be used, for example, to switch device mapping between Cartesian coordinates and angular movements. A photograph and additional details are given in Figure 73.

Specification	
Peak Force	9 lb
Minimum Force	2 - 3 oz
Continuous Force	1 lb
Force Resolution	0.035 oz
Backdrive Friction	2 - 3 oz
Range of Motion	Three revolute axes: yaw, pitch, and roll 90°
Position Resolution	Three revolute axes: yaw, pitch, and roll 1/45°
Dimensions	7 L x 9 H x 6 W in
Weight	4.5 lb
Interface	RS-232/422, Ethernet, Parallel I/O, A-D/D-A, custom

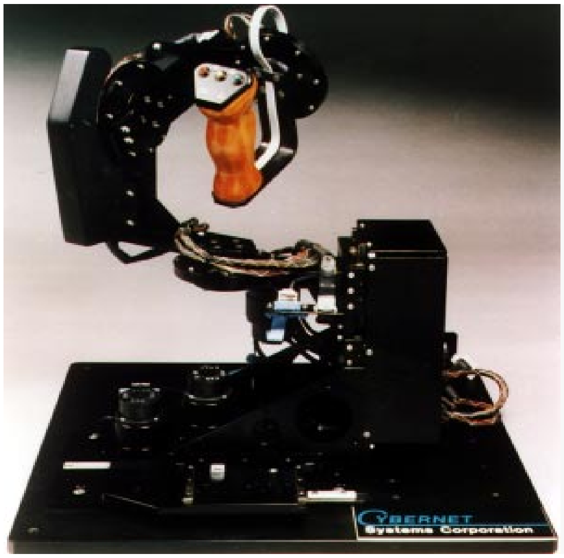
Photo courtesy of Cybernet Systems Corporation

Figure 73. PER-Force 3DOF

PER-Force 3DOF comes with a complete MS-DOS C development environment to support control system modifications and the development of custom interface drivers. The price of PER-Force 3DOF with PC-based controller is $9,995.

6.2.2.8 PER-Force Handcontroller and Finger Forcer Option

Originally designed for use in the Space Station, Cybernet Systems Corporation's PER-Force Handcontroller is a small device that provides the user with a motorized handle with which to position robots, or virtual objects, and through which 6 DOF force feedback is provided. The handle resembles an aircraft-type sidearm-control grip with three cueing buttons, an analog trigger, and a palm-activated deadman switch. Six brushless DC servo motors are used to provide force feedback on each of the 6 axes, although lower cost versions of the device are available for 2 to 5 axis operation. The handcontroller can be operated in various modes: force-position scaling, position-position lock, rate-position orientation lock, and user-programmed axis lock. A photograph and further details are given in Figure 74.



Specification

Output Force	Max 20 - 25 lb, min 2 - 3 oz
Force Resolution	12 bits
Range of Motion	Three linear axes, 4 in; three revolute axes yaw, pitch, and roll 90°
Position Resolution	0.0003 in each linear axis, 1/90° each revolute axis
Backdrive Friction	5 oz on linear axis
Handcontroller Weight	25 lb
Handcontroller Size	14.8H x 14.8W x 10.8D in
Interface	RS-232/422, Ethernet, Parallel I/O, A-D/D-A, custom

Photo courtesy of Cybernet Systems Corporation

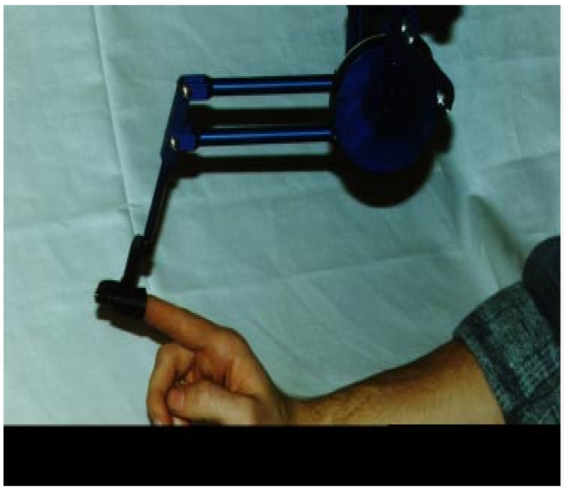
Figure 74. PER-Force Handcontroller

The PER-Force Handcontroller is controlled by the PER-Force Universal Robot Motion Controller, itself a 486-based PC, that provides an interface to any MS-DOS/Windows, VME, Mac, or Unix-based machine. Two development libraries come with the Handcontroller and Motion Controller, one to use in programming the controller directly, and the other for use on a host machine to which the controller is interfaced. These libraries support control system modification, reconfiguration, and interfacing; they are available in both C and X Windows formats. Additional software is provided to facilitate passing force commands to the controller. PER-Force Handcontrollers, with the PER-Force Universal Robot Motion Controllers, are custom-made and no general price information is available.

Cybernet is currently developing an additional product, the PER-Finger Forcer, that can be attached on the top of the Handcontroller to provide force feedback at the fingertips for up to four fingers and thumb. This device monitors finger position in 2 DOFs for each finger and 3 DOFs for the thumb, providing 6 DOF force feedback using miniature brushless DC servo mechanisms. The device uses thimble-like structures to grasp the user's hand, and each finger and thumb is inserted into small stirrups at the end of the effector mechanisms. It supports the full range of finger motion. The peak force output on each axis is 2 lbs, with a continuous force output capability of 0.3 lbs, and minimum force output of less than 1 oz. As with the Handcontroller, the PER-Finger Forcer supports various control modes and is driven by a PER-Force Universal Robot Motion Controller interfaced to a serial port on any MS-DOS, VME, or Unix-based computer. The PER-Finger Forcer is expected to be released on the market in Spring '96. The 3 DOF version is expected to be priced at $9,995 and the 6 DOF version at $59,000.

6.2.2.9 PHANToM

Developed at MIT and now marketed by SensAble Devices, Inc., the PHANToM Haptic Interface Device is a desk-based device that provides force feedback to a thimble slipped over the user's fingertip. Optical encoders are used to measure the position of the user's fingertip, with one encoder being mounted on each of 3 DC brushed motors. These motors generate forces in the *x*, *y*, and *z* coordinates, and the torques are passed through a pre-tensioned cable transmission to the stiff, lightweight aluminum linkage that supports the thimble. The thimble can be replaced by pen-like objects such as a stylus or scalpel to provide a tool-based interface to a VE. Specification details are provided in Figure 75. This figure also shows the initial version of PHANToM, which is priced at $19,00. A larger version of the device, called PHANToM 1.5, with a 300% larger working space is also available for $24,00. Even larger versions that support a full-arm workspace are available to selected research groups.



Specification	
Peak Force	10 N
Continuous Force	1.5 N
Force Resolution	12 bit
Max. Object Stiffness	35 N/cm
Position Resolution	400 dpi (0.07 mm)
Inertia at Tip	50 - 100 g
Backdrive Friction	0.1 N
Latency	0.01 msec.
Bandwidth	250 Hz
Workspace	8 x 17 x 25 cm

Photo courtesy of SensAble Devices, Inc.

Figure 75. PHANToM

PHANToM is controlled by Silicon Graphics or 486 PC-based software and comes with a portable library of demonstrations that show how PHANToM can be used. This library is also a source of software models for various virtual objects (such as cubes, spheres, walls, and polygonally rendered objects), and additional models used for providing object properties such as texture and friction.

Two PHANToMs can be used simultaneously to support force feedback for a thumb and finger on one hand, or one finger on each hand. Additional PHANToMs can be used to provide, for example, force feedback for two fingers on each hand. All that is needed to support the use of multiple devices is special driver software that is available from SensAble Devices, Inc. This organization has also developed a system where two users, each with their own PHANToM, can cooperate in a shared virtual workspace, though this system is not yet commercially available.

SensAble Devices is currently engaged in developing additional software support for PHANToM, investigating issues in two-fingered grasping, and developing a system that supports force feedback for a third finger. A low-cost version of PHANToM intended for the mass consumer market is also under development and expected to become commercially available within the next couple of years.

6.2.2.10 SAFiRE

EXOS, Inc. developed and market a sensing and force reflecting exoskeleton (SAFiRE) that applies forces to the thumb, index finger, and wrist. The Phase II SAFiRE device has eight active DOFs: 3 DOFs on the thumb, 3 DOFs on the index finger, and 2 DOFs on the wrist. After investigations to determine a suitable mechanical system, linkages grounded to the forearm that apply 3-D Cartesian forces to the fingertips and palm were chosen. The endpoints of the manipulators for the thumb and index finger are attached to the fingertips, and include passive freedoms that allow for comfortable finger motion.

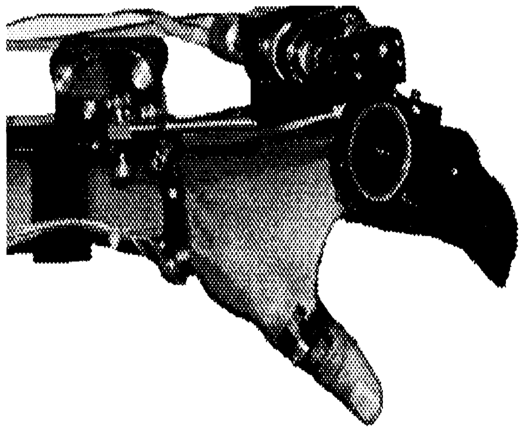
The SAFiRE device is actuated by DC motors that are remotized and connected to the device joints with a cable and gear transmission. Incremented optical encoders are attached to motors for measuring motor position and an Ascension Bird tracker is attached to the forearm to sense forearm position and orientation. Actuator packages are grounded to the forearm; tips of the manipulator are attached to the fingertips and to the palm via a cuff.

The basic electronics and control hardware consists of two dedicated high performance processors and a Silicon Graphics workstation. One processor handles dynamics simulation software and communications, while the kinematics and low-level device control software resides on the second processor. The VE display graphics and user interface module is implemented with the Sense8 package on the SGI workstation and communicates with the processors via parallel I/O on a SCSI bus. The dynamics simulation environment contains a number of objects that can be manipulated by the SAFiRE device. The kinematics software contains kinematic models of the SAFiRE device and the human hand, and is responsible for transforming joint angles and position information into Cartesian space for the dynamics and graphics modules, as well as converting Cartesian forces to motor torques.

For desktop applications, an optional boom is available to counterbalance the weight of the device. A photograph and some specification details are given in Figure 76. SAFiRE devices are built to order and no general price information is available.

6.2.3 Current R&D

As with tactile interfaces, development of force feedback devices for teleoperation systems has provided the initial starting point for the technology discussed in this section. Indeed, there are many aspects in which the technology used for providing force feedback in VEs is the same as that used for teleoperation.



	Specification	
Force/Torque	Thumb	1 lb max
	Index Finger	1 lb max
	Wrist	2 lb max
Joint Motion	Each force reflecting flexion DOF 90°, finger radial/ulnar deviation 30°, circumduction of thumb 45°	
DOF	Thumb	3
	Index Finger	3
	Wrist	2
Friction	Approx. 4 oz-in or less	
Backlash	<1°	
Device Weight	<4 lbs	
Interface	Custom	

Photo courtesy of EXOS, Inc.

Figure 76. SAFiRE

The remainder of this section discusses the work of individual research groups. While it is unlikely that the identified efforts are the only ones currently underway, they do form a representative set. In addition to those presented below, there were two research efforts for which detailed information was not available. The first was the development of an arm exoskeleton system for the presentation of force feedback by Dr. Bergamasco at the Sculo Superiore in Pisa, Italy. The second is Dr. Robert Anderson’s development of software libraries that support the creation of virtual forces. Dr. Anderson is with Sandia National Laboratory.

6.2.3.1 Boeing Computer Services

Led by Dr. William McNeely, researchers at Boeing Computer Services are pursuing the development of a high-fidelity force feedback capability that is scalable to the range of body motion and work volumes encountered in the simulated design, manufacture, and operation of aerospace vehicles. This work employs the concept of robot graphics in which forces are served by robotic mechanisms that are not attached to the body.

In 1994 Boeing researchers conducted proof-of-concept demonstrations of this approach, illustrating how it might be applied to control panel prototyping. As shown in Figure 77, the user, wearing a HMD, stands before an empty physical panel with a rectangular grid of holes. The HMD displays a control panel designed using four different types of controls, and this image is 3-D registered with the physical panel. Whenever the user reaches out to contact a virtual control, the associated hand motion is detected and the contact intention deduced. A robot then quickly moves a physical control of the right type to the anticipated point of contact, pushing it through the hole in the physical panel and holding it there to satisfy user contact. Although only one finger was videometrically tracked, the entire hand received appropriate force feedback, for example, in pushing a button or turning a knob.

Figure 78 shows the first-person view of this process. The layout of controls can be edited by touching controls and special command points. This system demonstrated a natural and effective VE interface and validated the robot graphics approach. Full immersiveness was not achieved with the available apparatus, however, primarily because of inadequate haptic-visual registration.

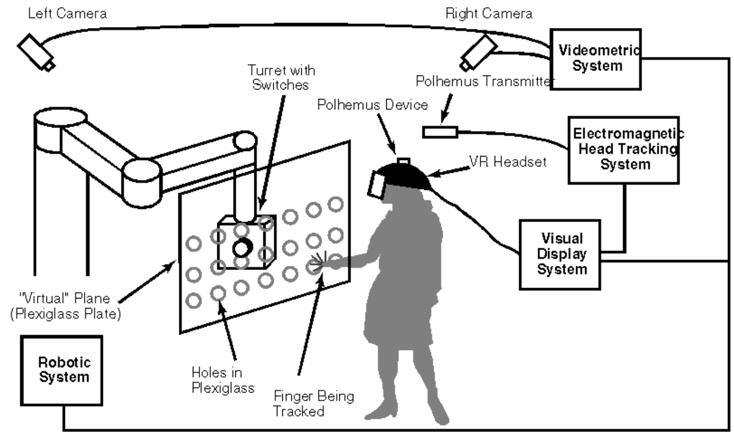


Figure 77. Robotic Graphics Proof-of-Concept System Overview

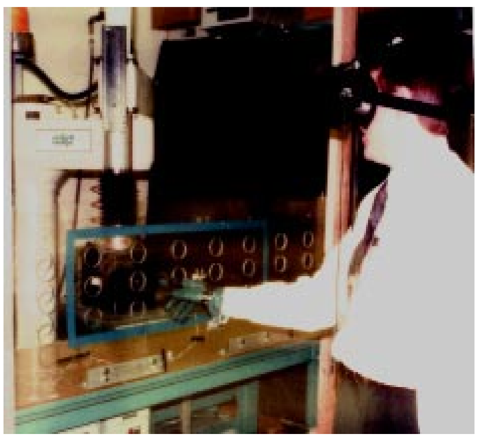


Photo courtesy of Boeing Computer Services

Figure 78. Robotic Graphics Proof-of-Concept System

In the future, this group hopes to investigate the scalability aspects of robot graphics, a central concern in aerospace VE applications. Long-term objectives include providing a useful human work envelope of about 4 cubic meters, human flexibility of up to 70 DOFs using multiple low-DOF robots, and movement over a large floor space using mobile robots and/or treadmills. One promising solution requires the user to wear a lightweight passive exoskeleton that provides body tracking and serves as a mechanical interface and safety barrier to robots that surround the user. The latter dynamically attach and detach to special points on the exoskeleton and provide forces and torques as dictated by the VE. These attach points would be handed off from robot to robot as required to avoid such problems as mechanical singularities and robot-robot collisions.

Another key development area is the robot graphics "middleware" to support the design-driven selection and placement of static display elements, and rapid prototyping/approximation/deployment of active display elements. Work in this area is also addressing such concerns as human motion prediction, multi-robot choreography, and accident avoidance. It is thought that much of this infrastructure could be developed and safety tested using software simulation in an auxiliary VE testbed.

6.2.3.2 Computer Graphics Systems Development Corporation

Computer Graphics Systems Development (CGSD) Corporation researchers also are investigating the potential of robotic graphics. Following a feasibility study conducted in 1994, these researchers are developing a prototype virtual aircraft cockpit that includes realistic simulation of the forces and tactile sensations of operating instrument panel controls. Physical fixtures are used for the primary controls (throttle and joystick) and a stereo image of the cockpit, including the user's hand and the out-the-window scenery, is presented in a HMD. The virtual cockpit is intended to provide a highly reconfigurable simulator for design verification and, ultimately, for flight training.

Requirements for the Force and Tactile Feedback System (FTFS) were determined by analysis of cockpit videotapes and lab experiments. The FTFS is a robotic positioning system that tracks the user's hand, anticipates which control is to be actuated, and moves an example of the control into position to be actuated. The positioning mechanism has, on a flat panel, various types of switches and knobs representative of instrument controls, including a number entry keypad. The system provides for positioning of controls in 3 axes and is designed to provide the high positioning speeds needed for realistic operation as a simulator. The user signals his intent to operate a control by reaching for that control: tracking his hand and fingers, the computer performs extrapolations to determine which control is desired. The panel does its final positioning in less than 50 msecs, so that the control is stationary before the user touches it. The workspace of the prototype FTFS is roughly 48 inches long, 30 inches high, and 6 inches deep. The controls are positioned to an accuracy of about 0.003 inches. Large motors are needed to move the panel quickly, so the controls are inherently stiff, able to resist over 10 lbs of force without perceptible motion. Safety is a major concern of the design and is the first concern of the development process. Redundant mechanisms are being incorporated to prevent user injury and a rectangular coordinate positioning system is used which cannot intrude into the user's space. The positioning device, when complete, could be coupled to any host simulation. It could also be used with varying visual systems. The preferred interface is dedicated Ethernet.

The FTFS is currently under construction with sponsorship from the US Army Simulation Training and Instrumentation Command (STRICOM). Completion of the prototype is expected by the end of 1996.

6.2.3.3 Hokkaido University, Japan

Led by Dr. Shuichi Ino, researchers at Hokkaido University are developing a system to provide force feedback to an elbow joint. For this, they have developed a metal hydride actuator which uses temperature changes in a metal hydride alloy to control the pressure of hydrogen gas in a bellows system cylinder; the pressure is converted into a propulsive force. The actuator is lightweight (300 g) and compact (a cylinder 20.62 mm in diameter). Using a metal hydride alloy of 6 g, it can generate a power of 20 kgf, and lift a load of up to 10 kg to a height of 50 mm with a velocity of 9 mm/sec, the fall time is roughly equivalent. The actuator is noise-free and produces no sudden impact forces. Experimental trials have demonstrated that the display has similar variable compliance to the human elbow, and that this compliance can be smoothly controlled by a computer.

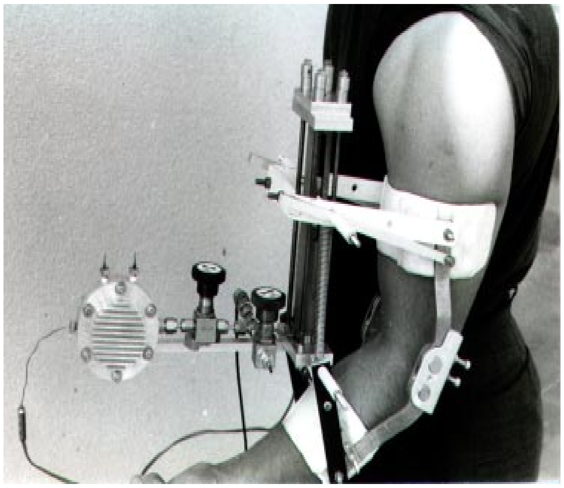


Figure 79. Elbow Force Feedback Display (Hokkaido University)

The researchers are investigating approaches for mounting a force display based on the metal hydride actuator on a human arm. Using the mounting shown in Figure 79, two psychophysical experiments were conducted to examine the usefulness of such a display (Shimizu, 1993). In the first experiment, the differential limen of the force sensation was measured at 400 gf and the ability of the display to provide smooth force changes to the elbow was demonstrated. In the second experiment, researchers compared the force sensation level produced by the display with that achieved by placing a real object on the forearm. In this case, the force sensation level difference between the sensation produced by the force display and that produced from a real object was less than the differential limen and, hence, unnoticeable.

Currently, the researchers are investigating parameters that can be used to provide realistic sensations of weight, resistance, and binding.

6.2.3.4 Massachusetts Institute of Technology, Artificial Intelligence Laboratory

Led by Dr. Ken Salisbury, researchers at MIT, Artificial Intelligence Laboratory, are pursuing two main areas of work for force feedback interface technology. The first area is concerned with further development of PHANToM (see Section 6.2.2.9). Here, much of the work lies in investigating how to move from the single point interaction provided by the current PHANToM device to more general paradigms for multiple finger interaction. The researchers are also looking at replacing PHANToM's thimble interface with passive tools and with 1 DOF tools such as power-driven tweezers. A near-term goal for this work is the development of a system that uses two PHANToMs, each equipped with tweezers, for reaching into a virtual scene, grabbing simulated body tissue, and passing the tissue from one pair of pliers to the other; this work is supported by the Advanced Research Projects Agency (ARPA).

The researchers also are looking at using PHANToM as a platform to support additional sensory modalities. One example of such a modality will be the ability to transmit high frequency vibrations to provide the user with object texture information. The researchers are also talking with CM Research Inc. (see Section 6.1.2.4) about using CM Research technology in providing temperature feedback to PHANToM users.

The Navy Air Warfare Center Training Systems Division (NAWCTSD) is supporting MIT in an initial, practical use application of PHANToM force feedback. The system under development will use a virtual electronic board (comprised of rigid objects) and virtual probe to provide training for electronic technicians. A possible second application will be in bomb disposal training.

The other major area of research is in the development of software technologies. Here one effort is looking at haptic rendering, that is, the process of computing and generating forces. The overall goal is to develop a framework that can represent shapes, bulk properties, and multiple object interactions. Focusing on point interactions, the researchers have developed algorithms for rendering object contact forces, contact persistence, and impedance. They have found that if force information is presented with sufficient bandwidth and resolution, they can produce effects that are perceived as tactile sensations and, exploiting this, have also developed algorithms to render object surface properties such as curvature, texture, and friction. Different techniques for rendering overall object shape are being pursued; vector field techniques have already been implemented and the researchers are currently working with a constraint-based method they call the god object method. Algorithms for rendering non-homogeneous materials are under development. These support efficient implementation by allowing rendering to be limited to a local "window" of surface representation data. (Methods for the haptic scanning of surface property data based on force scanning are also under development.) The current methods used in rendering non-homogeneous materials apply the B-spline surfaces geometric modeling technique, though the use of potential field methods is being explored. In the course of this effort, the researchers have developed several demonstration applications, including a virtual control panel, a needle biopsy simulator, a tissue palpation system, and a simple virtual world where two PHANToMs are used to manipulate building blocks. Ultimately, this work will result in a haptic renderer that can accept CAD data as input and so facilitate construction of virtual worlds that exhibit a range of object properties and object interactions. The current prototype renderer supports haptic rendering for simple stationary objects. Future work on object rendering is expected to look at potential energy function representations.

Another effort concerned with software technologies involves the development of a reduced fidelity model for compliant objects that can be run in real time. Finally, as part of the ARPA task, the researchers are defining models of human organs and tissues that can be used to provide information about how these body parts "feel." Once the model parameters and structures have been determined, data will be collected to build a library of models that can be customized to particular patients as needed.

6.2.3.5 Massachusetts Institute of Technology, Department of Mechanical Engineering

At MIT, Department of Mechanical Engineering, researchers under Dr. Ian Hunter have been undertaking a large-scale effort to develop a system for eye surgery that exploits the capabilities of both teleoperation and VEs[1]. The system is being developed as an experimental testbed that could be used to study the effects of feedforward and feedback delays on remote surgery. It also is intended for use in research on how mechanical and visual telepresence can enhance the accuracy and dexterity of microsurgeons.

The teleoperation part of the system allows a surgeon to perform surgery using a teleoperated microsurgical robot (MSR-1) master and slave. Visual, mechanical, and auditory information is exchanged between the master and slave. With respect to visual information, the surgeon uses an HMD to orient the stereo camera system observing the surgery and to feedback images from the camera system to either the HMD or an adjacent screen. The surgery is performed using pseudo tools supported on active limbs mounted on a mechanical master. The surgeon's movement of the pseudo tools is scaled down, by 1 to 100 times, and transmitted to the microsurgery tools operated by the mechanical slave. Forces acting on the limbs of the MSR-1 slave are transmitted back to the surgeon, scaled up appropriately, via the pseudo tools on the MSR-1 master. Additional information is provided audially as a stereo tone whose amplitude and/or frequency is a function of the forces exerted at the tool-tissue interface. The computer system that controls the equipment enhances and augments images, filters hand tremors, performs coordinate transformations, and performs safety checks. The primary computer hardware is two IBM RISC System/6000 workstations.

The mechanical parts of the MSR-1 system, master and slave, employ six direct-drive rotary electromagnetic actuators for each active limb. Each set of six actuators is arranged in a redundant parallel configuration that supports motion in three linear and two rotary DOFs. Force and displacement transducers are integrated into the actuators. Figure 80 provides some details about the mechanical master and slave, including a photograph of the master device. The VE part of the system centers around a detailed continuum model of the eye anatomy, mechanics, and optical properties, supported with a less detailed geometric/mechanical model of the face. Mechanical finite element models of structures in the eye make it possible to calculate and display the deformation of tissue as it is manipulated, and to calculate forces to be fedback to the mechanical master. Together with a computer simulation of the MSR-1 slave, these models provide a training environment where the surgeon can practice with the use of the MSR-1 system and plan surgical procedures. Active mannequin faces are used for testing the microsurgical system and training surgeons in its use. The VE also plays a role here in providing input to the machining process used to construct a mannequin face.

Currently, further work on MSR-1 is awaiting the additional investment needed to support refining the existing prototype system and conduct testing in a real surgical environment. Meanwhile, these researchers, funded by ARPA, are developing a system to support heart surgery, HSR-1. The new system is closely based on the MSR-1 and will have

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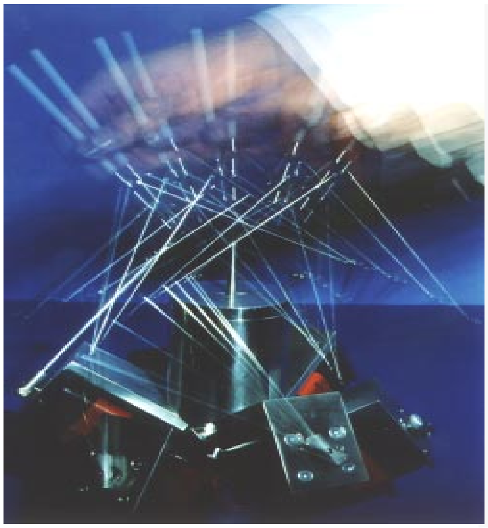
[1] This work was started at McGill University, Department of Biomedical Engineering, in cooperation with the School of Physical and Occupational Therapy at McGill University, and with the departments of Mechanical Engineering and Engineering Science at the University of Auckland, New Zealand.



Specification	
Peak Force (Master)	~2 N
Force Resolution (Slave)	<5 mN
Position Resolution (Slave)	<1 µM
Update Rate	5 kHz
Workspace	~25 mm diameter sphere

Figure 80. MSR-1 Mechanical Master/Slave

similar support for force feedback to the surgeon. It is currently in the early stages of development.

6.2.3.6 McGill University, Canada

Dr. Vincent Hayward at McGill University, Research Center for Intelligent Machines, is leading researchers in the development of haptic devices. One of these is a 6 DOF, optionally 7 DOF, force-feedback interface device intended for use in VEs and teleoperation. Called the Stylus, this device derives its name from its intended use as a small handle held with a precision grasp. In order to determine the requirements for such a device, these researchers have undertaken a number of experiments designed to provide insight into how well the human hand can discriminate the direction and nature of small motions (Hayward, 1995). Using a specially designed 6 DOF stimulator able to vary the amplitude, direction, and nature of small motions, subject sensitivity was found to vary greatly with training. In certain conditions, some subjects were capable of discriminating between two consecutive motions vibrating across orthogonal directions at up to 80 Hz, frequencies after which the motion was perceived as simply vibration.

Studies with another specially designed piece of equipment, a 2 DOF haptic device named the Pantograph, were conducted to determine an appropriate workspace for the Stylus. Results here led the researchers to decide on a work volume of 10 x 10 x 10 cm and an angular workspace on the order of 90° of pitch and yaw, with a roll of 180°. Additional studies with the Pantograph intended to characterize device factors that best transduce sensations of shock and hard contacts, found that the acceleration capability was probably the most useful factor. Additional requirements for the device were derived from the literature. These include requirements for a wide frequency response, high levels of accuracy in presenting forces, mechanical impedance that can be programmed over several orders of magnitude, and precise dynamic response up to 50 - 100 Hz. For its physical structure, the desktop Stylus device uses a single stage design with grounded actuation coupled by a combination of polymeric tendon transmissions and linkages to the active end. A separate actuator pack employs conventional electric motors. Custom-designed sensors based on optical techniques are used to measure displacement and forces.

A prototype device, see Figure 81, has been developed. This device provides 3 DOFs for displacement, 3 DOFs for handle orientations, and 1 DOF for pinching motions. Current work is involved in developing a driver for the Stylus that supports an analog interface to a PC. Other ongoing work involves further investigation of human factors and ergonomic issues for haptic interfaces. This work will include experiments investigating, for example, specific frequency and force requirements for particular applications.

Figure 81. 7 DOF Stylus (McGill University)

Currently, McGill University is working with MPB Technologies Inc. in commercializing the Stylus under the name Miniature Hand Controller. MPB Technologies, Inc. are also preparing a commercial product of a highly similar device, called the Wide-Span Hand Controller, that will provide a 30 cm diameter sphere workspace.

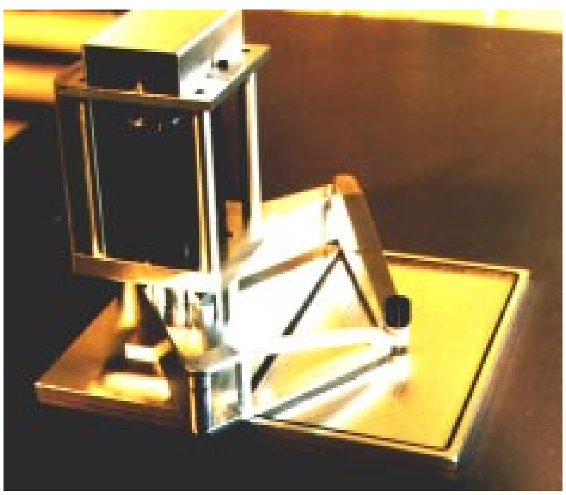


Figure 82. Pantograph (McGill University)

The Pantograph, mentioned previously, was developed in early 1993 as a collaborative effort with Christophe Ramstein from the Center for Information Technology Innovation, a research organization that is part of Industry Canada located in Laval, near Montreal. The Pantograph originally was designed as a computer interface in an effort to provide visually handicapped people access to graphical applications. A number of prototypes are operating at various laboratories in Canada in projects ranging from a surgical aid to human factors research. In one case, it is currently being compared with a conventional input device for use in microgravity environments. A picture of the Pantograph is shown in Figure 82.

In other work, Dr. Hayward, in collaboration with Dr. Raymond Hui, is supporting the Canadian Space Agency in the development of haptic interfaces for use in space and terrrestial applications. The design of these 3 DOF devices based on parallel linkages is motivated by the search for high structural transparency and simplified kinematics. Current work is looking at combining several of these low DOF devices, one per finger, to avoid the inherent complexity of higher DOF devices. Dr. Hayward is also proposing the development of a standard specification for haptic interfaces.

6.2.3.7 Ministry of International Trade and Industry, Agency of Industrial Science and Technology (MITI/AIST), Japan

Researchers at the MITI/AIST, National Institute of Bioscience and Human Technology, are developing a CAD system where the shape of 3-D surfaces can be evaluated using surface tracing and localized lighting schemes. Led by Dr. Yukio Fukui, this work started with modifying a conventional XY-recorder into a 2-D force feedback device. This device provided a 20 x 20 cm workspace in the horizontal plane with a 4 Hz response.

Experiments looking at the effectiveness of this device for virtual shape recognition have been conducted (Fukui and Shimojo, 1994). Four subjects were asked to perform discrimination tasks using either visual only (presented on a computer screen), haptic only, or both visual and haptic displays. The first task required selecting true circles from a series of deformed circles, where all the circles were visually presented as superimposed on a series of concentric squares. The second task required selecting pairs of lines that formed a straight line from a series of pairs that were jointed at angles other than 180°, here the lines were visually presented as superimposed on a background of lines connected at an angle. The results of the experiments showed that optical illusions commonly occurred when visual feedback was present, and the haptic only feedback condition gave a better mean performance than visual only feedback. When both types of feedback were provided, the mismatch of the visual and haptic information led to a performance similar to that achieved for visual feedback alone.

More recently, the researchers have developed a Cartesian 6 DOF force feedback manipulator. To achieve the desired stiffness, toughness, linearity, and economy, the manipulator uses bowl screws on a parallel movement for the *x*, *y*, and *z* dimensions, and worm wheels for rotation movement about these axes. The manipulator is driven using an AC servo motor to provide high speed and precise positioning (0.01 mm/pulse) and an external potentiometer is used to measure manipulator displacement. The forces exerted by the user are measured by a force sensor on the end-effector. The workspace provided is 30 x 30 x 15 cm with 200° about each rotational axis. Figure 83 shows a photograph of this device.

With the addition of a programmable mechanical impedance control, the 6 DOF manipulator is being used in studies investigating the spatial manipulation capabilities of the human hand. Additionally, it is being used as a 3-D input device for a CAD environment and early experiments have demonstrated its value for deforming virtual surfaces. Current work also is focusing on incorporating adaptive damping in the feedback loop to control device vibration and unstable movements.

6.2.3.8 Northwestern University

Led by Dr. Ed Colgate, researchers at Northwestern University, Department of Mechanical Engineering, are looking at several aspects of force feedback for interaction with VEs. They have developed a 4 DOF force feedback device and are currently investigating the issue of stability with respect to force feedback interfaces.

The 4 DOF force reflecting manipulandum provides a user with a joystick-type interface that can be mapped to a virtual hand tool in a VE, allowing the user to perform various mechanical tasks. Developed as a research tool, the device is designed to generate high impedances so that it can support the representation of such things as stiff springs and hard walls in the VE, as well as to exhibit low inertia and low friction. It uses direct-drive, parallel structures with closed-chain kinematics to provide translation in three directions and rotation in the horizontal plane. The workspace is free of singularities. High resolution optical encoders on the brushless DC-motor actuators and precision potentiometers on the non-actuated joints sense the angular position of the device joints to provide endpoint position and orientation of the endpoint (handle). Safety concerns are handled by mechanical stops and covers, hard-wired enable/disable circuitry and accelerometers, and software control. A photograph and some specification details on the device are given in Figure 84.

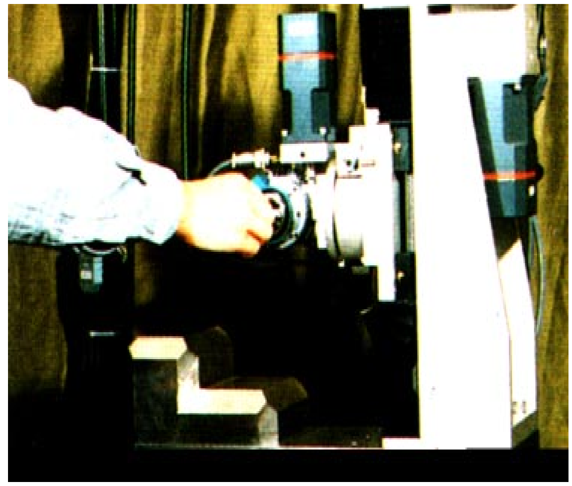
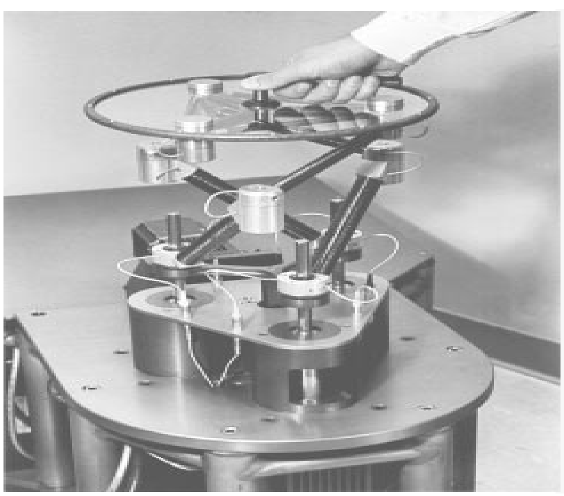


Photo courtesy of MITI/AIST, National Institute of Bioscience and Human Technology

Figure 83. Cartesian 6 DOF Force Feedback Manipulator (MITI/AIST)



Specification	
Peak Force	20 lbs
Continuous Force	10 lbs
Output Torque (Continuous)	12 in/lbs
Translational Range of Motion	Circle with 7 in diameter
Rotational Range of Motion	±45°
Vertical Range of Motion	3.5 in (not used)
Update Rate	250 - 1000 Hz
Latency	3 - 4 msec

Figure 84. 4 DOF Force Reflecting Manipulandum (Northwestern University)

The device is supported on a Inmos T805 Transputer with a VME bus backbone. Accordingly, the computations necessary to support the VE simulation and its user interface are performed on a network of distributed memory parallel processors. Four of these processors are dedicated to control of the force feedback device, performing the calculations necessary to determine endpoint position and velocity, and to determine the motor torques necessary to produce feedback endpoint forces and torque. The manipulandum is currently on loan to the National Aeronautics and Space Administration (NASA) Johnson Space Center, where is it being used to examine the feasibility of using VEs in the training of extra-vehicular activity (EVA) procedures.

The major thrust of the researchers' current work is in developing a physics-based approach for haptic interfaces that ensures that a VE simulation is governed by the conservation laws that operate in the real world. Using a 1 DOF force feedback device developed for this purpose, they are focusing on the requirements needed to guarantee stability when a user interacts with a VE. Although no method for guaranteeing system stability has yet been found, their work has shown the need for inherent physical damping in the haptic interface to increase its passivity, and digital filtering of the velocity signal to achieve high values of virtual damping. They have also found that high update rates increase the achievable stiffness of virtual walls. (Based on these findings, dampers have been introduced to the 4 DOF manipulandum already discussed.) Examples of current work in the area of stability include the definition of non-conservative stability conditions for systems involving unilateral constraints, and the development of methods for real-time simulation of multibody systems guaranteeing physical passivity. As part of their efforts in this area, the researchers are developing a haptic programming language that will facilitate the development and modification of VEs that provide physics-based haptic interactions.

As a first step in a study aimed at developing a theory of tool use to guide haptic interface, VE, and telemanipulator design, the researchers have conducted an experiment investigating the impact of environment damping (Millman and Colgate, 1994). Subjects were asked to position and maintain contact with a target region in a VE, where the target was distinguished by a rise or drop in the ambient virtual damping. The damping was simulated by the impedance of a 1 DOF manipulandum. Three visual feedback conditions were used: visual feedback was provided by showing the position of the manipulandum handle as a cursor on a screen, no visual feedback, and visual feedback showing the position of both the handle and target region on the screen. For very large differences in target and ambient damping, the results showed that haptic feedback alone gave performance almost equivalent to that attained when subjects could see the position of the hand and the target region on the screen. The subjects could detect the target region when the differences in the ambient and target virtual damping was greater than 2.27 N/m, though the researchers expect a greater level of discrimination is possible with equipment characterized by lower system noise.

In future work, these researchers hope to put the experience they have gained with force feedback interfaces to use in the development of a 6 DOF device.

6.2.3.9 Rutgers University

For several years, Dr. Greg Burdea has led a group of researchers at Rutgers University, Center for Computer Aids for Industrial Productivity, in the development of force feedback interfaces for grasping and manipulating virtual objects. The work has focused on the development of a portable dextrous hand master that has evolved through the Portable Dextrous Master with Force Feedback (PDMFF), the Rutgers Portable Force Feedback Master (RM-I), to the current Second Generation Rutgers Master (RM-II).

The central element of the RM-II design is the placement of four custom-designed pneumatic micro-cylinders on an "L"-shaped platform positioned in the user's palm, the whole being mounted on a thin leather glove. The actuators are additionally attached to the tips of three fingers and thumb, as shown in Figure 85, to deliver forces to those points. Attachments are by velcro strips to accommodate various user hand size. Position sensing for the fingers is integrated into the device by means of an assembly of two Hall-effect sensors mounted on the platform, an additional Hall-effect sensor mounted on each fingertip, and an infrared LED-phototransistor pair placed within each cylinder. A Fastrak position sensor mounted on the back of the hand provides wrist position and orientation. A separate interface box is used to house the proportional analog servo-controllers used to regulate the air pressure and, hence, the forces applied to each fingertip.

Specification	
Force Resolution	0.01 - 0.05 N
Max. Finger Output Force	17.2 N
Latency	100 msec
Bandwidth	14 - 16 Hz
Weight	80 - 100 oz

Figure 85. Second Generation Rutgers Master

Software supporting the RM-II has been developed to integrate this device (or the RM-I) into a complete VE interface. The VE system that currently uses this interface is hosted on a set of workstations connected via Ethernet and supports StereoGraphics LCD glasses. The VE itself consists of a room with perspective grids, a virtual hand, and a selection of virtual objects (ball, soda can, and spring). Object stiffness can be adjusted to model both elastic and plastic objects. Forces are calculated using Hook's Law, and gravity is modeled to allow objects to bounce off the walls. Grasped objects deform graphically when squeezed by the virtual hand. Present research is aimed at accommodating multiple objects in the same scene. The researchers plan to port this software to the Sense8 WorldToolKit Version 2.0 and to develop a stand-alone PC architecture for the force feedback interface.

Using this VE system, and the earlier RM-I, the researchers conducted a series of human factors experiments to test the usefulness of force feedback for VEs (Gomez, Burdea, and Langrana, 1995). In one experiment, the task was to grasp and manipulate a deformable ball without indenting it more than 10% of its volume. Eighty-four subjects participated, divided into six groups. Each group was provided with a graphical representation of the ball deformation plus some combination of force feedback, visual bar-chart of output pressures, and auditory displays. (The auditory feedback, presented through headphones, provided a sound frequency proportional to the current deformation of the ball and was used as a substitute for tactile feedback.) The first half of each group performed the task using a monoscopic display for the graphics feedback, the second half used a stereo display and active LCD glasses. Among the non-redundant feedback modalities, force feedback produced the best result. When redundancy was present, the force and auditory feedback combination was superior. Present experiments are aimed at repeating the trials using the newer RM-II, in order to compare it with RM-I performance.

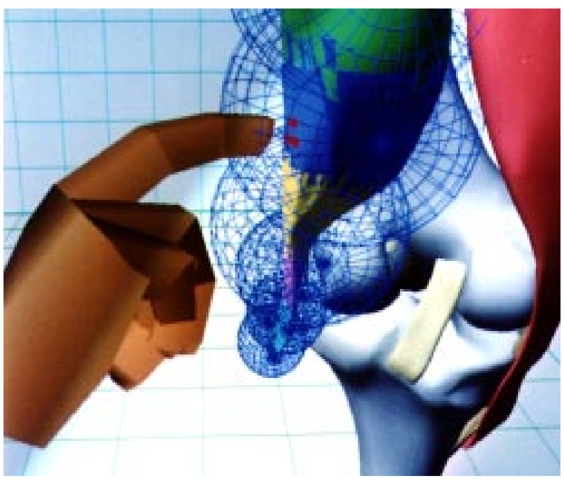


Figure 86. Virtual Knee Palpation System

Work is also underway to develop more general software support for the RM-II. This software is currently being used to support force feedback in a system for virtual knee palpation that can be used by surgeons to train and plan for knee surgery. For this application, geometry data for a complete knee joint was modified to support tissue deformation. A DataGlove is used for position sensing and the RM-II for tissue manipulation. A Sun 4/380 is dedicated to handling the force feedback for the RM-II, with the rest of the simulation being performed on a HP 755 CRX workstation. The VE itself supports three types of objects: a virtual hand, virtual knee, and room walls; the user's viewing perspective of the rendered scene can be adjusted using a 6-D trackball. A photograph of this VE is shown in Figure 86. Recent work has focused on the development of the collision detection and deformation algorithms and the proof-of-concept system currently supports one finger palpation of tissue compliance. The computational load imposed by shape modeling and calculation of force data has resulted in a low frame rate, between 3-5 frames/sec, and ongoing work is improving the simulation to allow increasing the frame rate to a minimum of 14 frames/sec, and providing a force bandwidth of 10-12 Hz.

Additional, and future, research is pursuing complex multi-fingered manipulation and the development of an RM-II application to support explosive handling in suitcase inspection at transportation facilities.

6.2.3.10 Suzuki Motor Corporation

At Suzuki Motor Corporation, Technical Research Center, researchers led by Dr. Yoshitaka Adachi are investigating the use of force feedback for manipulating the free-form surface of virtual objects. They have developed a simple distribution function algorithm for recognizing the interference between a 3-D cursor and virtual objects, and calculating the direction of reaction forces in real time. These forces are then generated using impedance control. The force feedback device they have developed to display the forces is called SPICE.

SPICE is a articulated mechanical structure with invariant and decoupled arm inertia and 6 DOFs. Each joint is driven by a direct drive DC motor capable of providing a wide range of torques. The arm structure and its mass distribution have been optimized through an evaluation of arm dynamics with a generalized inertia ellipsoid. Optical encoders are used to sense joint angles and so provide information on the position and orientation of the user-held grip. The grip provides the user with the means to interact in a VE, and a 3-D cursor is used to represent the user's hand. One microcomputer with a floating point co-processor is used to simulate the virtual haptic environment. Another microcomputer, with floating point co-processor and three vector processors, controls the force feedback device. The device and the various computers communicate via a VMEbus. A photograph and specification details for SPICE are given in Figure 87.

Specification

Peak Force	>200 N
Continuous Force	50 N
Force Resolution	0.1 N
Spatial Resolution	0.01 mm
Sampling Rate	500 Hz
Workspace	30 x 30 x 30 cm

Figure 87. SPICE

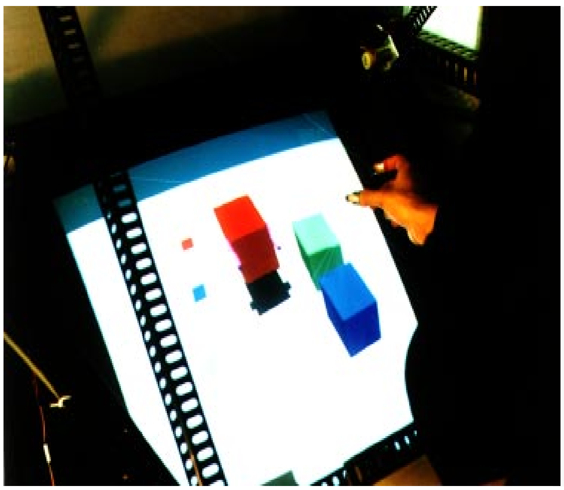
SPICE has been used in evaluating an approach for representing free-form stiff virtual objects. One of the limiting factors for the generation of stiff surfaces is sampling rate and this approach focuses on reducing the computational requirements needed for detecting collisions with virtual objects, so that the sampling rate is not reduced to unacceptable levels. Based on the position of the user's fingertip in the VE, a tangential plane that includes the point on the virtual object in the VE that is nearest to the fingertip is defined. The position and orientation of the virtual plane is updated at low frequency to accommodate finger movement. At the same time, collision between the fingertip and virtual plane is checked and, if necessary, a reaction force is calculated. The primary advantages of this approach are that it simplifies calculation of force vectors and allows detection of collisions to be computed independently from the impedance control of the force feedback device. Using SPICE, the researchers conducted an experiment to determine the frequency of impedance control required for effective generation of force sensations; for tracking on a stiff virtual wall, Adachi, Kumano, and Ogino (1995) report that an impedance control greater than 500 Hz was needed. The researchers also investigated the update rate required for the virtual plane when representing a curved surface in the VE. This experiment employed a virtual cylinder with a 75 mm diameter, an impedance control of 1,000 Hz, surface stiffness of 10,000 N/m, surface viscosity of 1000 N/m/sec, and artificial friction of 600 N/m/sec. A virtual plane update rate of 3.3 Hz gave the impression of a smooth curved surface when finger velocity was around 20 N/m/sec. A lower update rate (2.5 Hz) gave a feeling of a bumpy surface unless finger movement was slowed to 8 mm/sec.

A separate set of experiments, using SPICE, has been conducted using sensory evaluation methods to determine the impedance characteristics that make virtual push-buttons comfortable to operate. More specifically, these other experiments have examined the effect of physical parameters such as spring stiffness and damper viscosity for button pushing. The virtual button was designed as a massless plate backed by one spring, with a second spring and damper positioned under the first spring to provide the feeling of the bottom of the button. The first experiment in this series examined the feeling of the bottom of the button in terms of the sensory factors “stiffness” and “evaluation.” Here Adachi reports that in the case of low damper viscosity, the stiffness factor increased linearly with increases in viscosity and with increases in spring stiffness. At higher levels of damper viscosity, the stiffness factor was influenced by the viscosity rather than spring stiffness. No clear relationships between the evaluation factor and spring stiffness or damper viscosity were found. The second experiment examined the operational feeling of push-buttons, with respect to initial load and spring stiffness. It was found that the stiffness factor score increased linearly with increases in the initial load, buttons with a small initial load lacked of feeling of crispness in the button surface, and users did not like buttons that needed a large force to operate them. The final experiment in this series assessed the effect of incorporating a “click” feeling into the buttons. This sensation was introduced by increasing the reaction force as a button was pushed and at a given maximum value, in the middle of the push stroke, quickly decreasing the reaction force. The experimental results demonstrated that this type of clicking decreased the required operational force while keeping a crisp feel at the surface of the button.

Currently, SPICE is being used in a project to develop advanced user interfaces for CAD and 3-D modeling systems. One of the applications under development in this project is a 3-D sketchbook intended for use by plastic surgeons in preparing for orthopedic surgery.

6.2.3.11 Tokyo Institute of Technology, Japan

Researchers led by Dr. Makoto Sato at the Tokyo Institute of Technology, Precision and Intelligence Laboratory, have developed a force feedback device called the 3-D Spatial Interface Device for Artificial Reality (SPIDAR). For this device, the user inserts his index finger into a cap that is held by four strings. Using a system of pulleys and motors, string lengths provide a means for measuring finger position, and the tensed strings provide for the presentation of force sensations at the cap. SPIDAR is controlled by a DX4-100MHz PC. A photograph and some specification details are provided in Figure 88.



Specification	
Peak Force	16 N
Continuous Force	4 N
Force Resolution	4096 steps
Max. Object Stiffness	10,000 N/m
Position Resolution	0.025 mm
Update Rate	1600 per sec
Inertia	50 gcm2
Workspace	90 x 60 x 60 cm

Figure 88. SPIDAR

The utility of the force feedback provided by the SPIDAR was examined in an experiment where three subjects used SPIDAR to deform a virtual cup-shaped object into an object shaped like a soccer ball (Ishii, 1994a). In the absence of force feedback, the subjects found it difficult to complete the task and often gave up; with force feedback, the task was completed within a few minutes.

A version of SPIDAR, SPIDAR II, that provides force feedback to the thumb and index finger has also been developed. Two initial experiments that looked at the effectiveness of SPIDAR II for pick-and-place tasks have been performed (Ishii, 1994b). For these experiments, the VE was generated by a Silicon Graphics INDIGO2 XZ, with a visual display presented on a screen and viewed by a user wearing stereoscopic glasses, and SPIDAR II providing force feedback. In this configuration, the refresh rate for the force generation was 100 Hz and forces ranged from 0 - 4 N, with an incremental step of 0.016 N. The experimental task was to position a 5 cm^3 block on a target circle marked on a raised platform. For the first experiment the block weighed 50 g, and for the second experiment the weight was varied (20, 35, 50, 70, 100, and 150 g). Three subjects were used for each experiment. The results of the first experiment showed that the provision of force feedback did not greatly impact overall task completion time. The pick-up and positioning parts of the task were performed more quickly with the guidance provided by force feedback, but the moving part of the task was slower with force feedback than without it, perhaps due to the effort required to move a virtual object that possessed weight. The force feedback did tend to result in more accurate positioning of the block on the target (accuracy was measured as the distance between the center of the bottom of the block and the top of the platform). The results of the second experiment showed that increasing the block weight slowed task completion time; as in the real world, a heavier object is more difficult to move and position than a lighter object. The optimum block weight was between 35 and 50 g. Additional experiments are being conducted to study the representation of object weight in a VE.

With respect to providing force feedback to both hands, ergonomic experiments designed to discover appropriate positioning between a user and SPIDAR devices have been performed. Based on the results of these experiments, a new version of SPIDAR is being developed that allows the use of both hands in combining 3-D objects to construct new objects. Initial usage has shown that this system does, indeed, support users in tasks that require two-handed manipulation directly, or the use of two hands in cooperation. Current work includes enhancing this system to support delicate operations and providing auditory feedback.

A closely related effort is focused on the use of SPIDAR to support a virtual workspace for the collaborative design of 3-D objects. Accordingly, this virtual workspace supports both face-to-face interaction between a pair of participants and interaction between a participant and an object. It is structured around what the researchers term a "dialog space" and an "object space," with participants switching their attention between these spaces as required. The specific design requirements imposed for this system are: (1) direct manipulation using both hands, (2) provision of force feedback, (3) support for pick-and-place operations on objects, (4) a wide range of hand motions with a significant number of DOFs, and (5) easy and safe operation, using an inexpensive system. A prototype system with single hand direct manipulation has been developed, supported by a local area network. Each participant is provided with a SPIDAR and two screens in juxtaposition: one screen for the face-to-face communication between the participants, and the second for display of the VE where 3-D objects are designed. While only one participant can actually manipulate an object at any one time, both can be in contact with the object so that the second participant can feel the forces exerted by his partner. Microphones and audio speakers are used both to support voice communications and to present sounds of object collisions. In a small-scale experiment, four pairs of participants performed a hand-over task, where a virtual block is passed from by one participant to his partner. The force feedback provided by SPIDAR enabled quick and accurate passing of the block. There were no instances of the block being dropped, as frequently occurred when no haptic feedback was provided. More recent and ongoing work in this area is focusing on multi-user collaboration, support for multiple virtual objects, and networked force feedback interactions in the presence of time delay. A demonstration for networked VE is under development, this is a virtual tennis game using two enlarged SPIDARs (with a working space of 3 m^3) connected to each other.

6.2.3.12 University of North Carolina

Some of the earliest work in force feedback displays for VEs was conducted at the University of North Carolina (UNC) at Chapel Hill, Computer Science Department, and these researchers, led by Dr. Fred Brooks, continue to be active in this field. The overall objective of the work is to investigate and develop methods for providing high quality force feedback in real applications.

The Force-Feedback Project, which began in 1967, first focused on the development of a system to support scientific visualization in the area of molecular docking, the Docker application. This application provides graphic (wire-frame) representations of molecules and their inter-atomic forces to allow a user to adjust the relative position and orientation of molecules while searching for minimum energy binding sites. A series of systems have been developed, evolving from a 2-D system, through a 3-D system and a 6-D system for a simple docking task, to a full 6-D molecular docking system called GROPE-III. These later systems have employed a modified Model E-3 Argonne Remote Manipulator (ARM) for force feedback display. (The ARM is a 6 DOF device developed at Argonne National Laboratories for teleoperation applications. It uses a hand-grip display, with joint action at the shoulder and outward. It provides a workspace of approximately 1 m^3. Forces are generated by AC electric servo-motors and joint positions are measured using analog potentiometers.) The researchers have made several modifications to the ARM, including the addition of dials for controlling the twistable bonds found in some drugs. In the GROPE-III application, the force-feedback device runs on a dedicated PC with a force update rate of 15 Hz. The visual feedback is generated by a Silicon Graphics Onyx with a Reality Engine, and the displays are presented via a StereoGraphic Crystal Eyes unit. GROPE-III runs in synchronous mode, pausing the simulation as necessary to wait for position measurements to be collected, and the resultant forces calculated and sent to the ARM for display to the user. Figure 89 shows a user working with the molecular docking application.

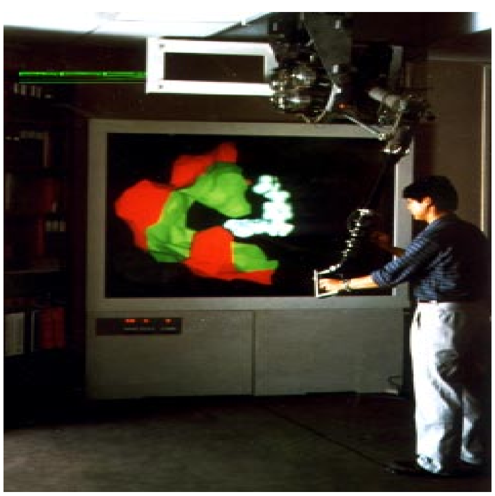


Figure 89. Molecular Docking Virtual Interface

Researchers used GROPE-III for an experiment that looked at the effectiveness of force feedback display in a complex molecular docking task (Brooks, 1990). The subjects for the experiment were twelve experienced biochemists. The results showed that the 6-D rigid-body docking part of the task was about 30% faster with the force feedback as opposed to only visual feedback, and drug trajectory paths were 41% shorter with force feedback. However, while the overall elapsed time performance with the force feedback was improved, the different was not significant. The reason for this is believed to be due to the large amounts of thinking time the task required. If the times when the subjects were just thinking, that is, not manipulating anything, are subtracted out, the overall time for the 6-D docking task was 1.75 times faster with force feedback than without. This, and other, experiments have shown that force feedback can facilitate the performance of molecular docking tasks. However, the researchers believe that the major contribution of GROPE-III lies in its ability to give biochemists deeper and new insights into molecular docking issues.

Recently, the researchers have installed a custom-designed PHANToM (6 DOF position sensing, 4 DOF force feedback) as an alternative interface to the molecular docking system. The system now is primarily used at the UNC for demonstration purposes, and is in occasional use by UNC biochemists. It has also been installed at Wright Patterson Air Force Base (WPAFB), Materials Laboratory, where is it being used to investigate the packing of molecules in liquid crystals. (The WPAFB implementation uses a Cybernet PER-Force arm for force feedback.)

Another application under development at UNC supports manipulation of flexible molecules. The initial version of this system, called SCULPT, does not provide force feedback. It is marketed by Interactive Simulations Inc. and in use at Duke University to support the design of amino acids that can hold molecules to required shapes. UNC researchers are extending the system to include force feedback using the ARM and PHANToM.

One of the current focuses of the Force-Feedback Project has been the development of a software library to support the use of force feedback devices. This library accepts force inputs specified in Newtons and torques specified in Newton-meters, and provides position information in units of meters in Cartesian coordinates and orientation in radians. It is designed to be device-independent and the Application Programmer Interface is intended to support its use by application developers unfamiliar with force feedback technology. The library has a client-server structure so that the client portion can run on the same computer as the application and the server portion run on a computer dedicated to supporting the force feedback device. Currently both the ARM and PHANToM devices are supported.

A second major area of research has been the Nanomanipulator (nM) application, being performed as a collaboration between UNC Departments of Computer Science and Physics, and the Department of Chemistry at the University of California, Los Angeles. The goal of this work is the fabrication of nanometer-scale structures in the study of materials relating to quantum effect devices. Here the ARM, and more recently PHANToM, have been used in supporting a range of scanning probe microscopes. The initial implementation provided a VE interface to a scanning tunneling microscope, and later implementations have supported an atomic force microscope. As a real-time visualization application, these systems present a rendered 3-D color surface image to the user, who can then view and feel the surface representation using the force feedback interface and, with the atomic force microscope, make direct surface modifications. Operation of the atomic force microscope virtual interface is illustrated in Figure 90. The display tools support surface scaling and grabbing, flying, and lighting adjustments. Measurement functions are supported by allowing the user to superimpose a reference grid on the surface. Standard VCR-like controls allow the capture of data for off-line analysis. The suite of surface modification tools support area or selective sweeps, line drawing, and engraving.

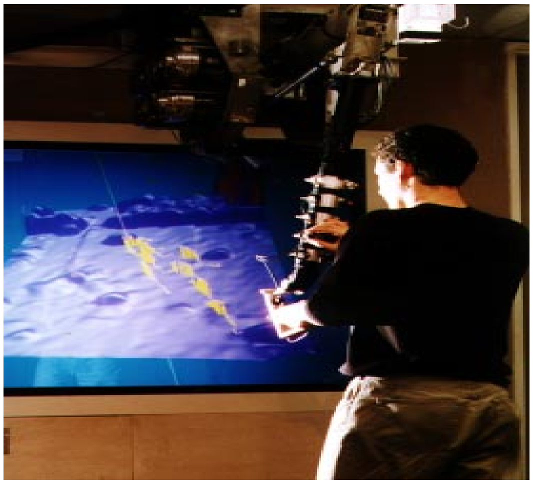


Figure 90. Operation of the Atomic Force Microscope Virtual Interface

The effectiveness of the nM VE interface with force feedback has been demonstrated in several instances. In its first test, researchers investigating a graphite surface were able to identify sheets of graphite tilted up out of the surface that had been unnoticed using conventional visualizations. Subsequently, use of the nM led to the discovery of a new mechanism for surface modification. In an experiment in the manipulation of colloidal gold particles, users were able to maneuver selected particles without disturbing the surrounding material in a short time, actions which may not be possible using conventional tools. The nM also has been used for the dissection and movement of the Tobacco Mosaic Virus. Current work with the system is focusing on better surface representations using the PHANToM device.

6.2.3.13 University of Tsukuba, Japan

Dr. Iwata at the University of Tsukuba, Institute of Engineering Mechanics, developed the HapticMaster, a desktop force display now commercially available from Nissho Electronics Co., see Section 6.2.2.5. Researchers at the university are using this device to develop a force feedback environment that supports the design of 3-D shapes.

A pen-based device has also been developed and is being used in interactive deformation of free-form surfaces. For this application, the user is provided with a toggle switch that allows the pen to be put in a special mode that adjusts the position and orientation of the surface, and a slider that is used to select the appropriate deformation area. The reaction forces are displayed vertically to the original surface and increase proportionally to the displacement of the pen point. The researchers developed a sine curved-based deformation algorithm for free-form surfaces and, when using the pen interface to push or pull on the surface while holding down the pen button, the user is able to feel the reaction forces. Use of the HapticMaster for interactive deformation of free-form surfaces also has been demonstrated.

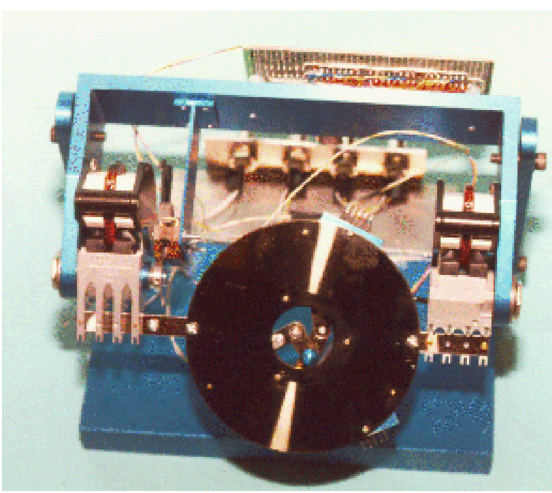
Another example application is volume visualization. Here, visual and force feedback are integrated to support multi-dimensional representation of volumes. This system includes both a HMD, with graphics generated by a Silicon Graphics IRIS INDIGO2, and the force display. The pen-based device acts as a 3-D pointer to provide user input to the system. In an experiment to evaluate the effectiveness of the force feedback interface in a volume classification task, three subjects were asked to count the number of high density cores (1 to 5) embedded in a less dense volume, and then point out each such core. The results showed that the provision of force feedback doubled the accuracy of the pointing task. A second experiment using 6 cores and 4 subjects gave similar results. Current work in this area is examining different methods for mapping voxel data to force and torque, cross influences between force and torque sensations, and further applications of volume haptization.

Dr. Iwata is also engaged on the development of a VE interface that will permit a user to walk in virtual space; this work is discussed in Section 7.2.2.7.

6.2.3.14 University of Washington

The University of Washington, Department of Electrical Engineering, has three separate efforts underway that are concerned with providing force feedback for VEs. One effort is developing a pen-based force display, another is developing a high bandwidth force display, and the third effort (being performed in conjunction with NASA, Johnson Space Center,) is investigating the use of robots in providing force feedback. This work is under the leadership of Dr. Blake Hannaford.

The prototype pen-based force feedback device has been developed as a tool for precise manipulation in a VE, or for scaled telemanipulation. The design goals for the device were driven by the requirements for medical microsurgery. Chief among these were requirements for no backlash or lost motion, minimum friction, and minimum inertia. The user can use the device via fingertip or with a pointed object such as a pen or scalpel. The actual device is a 3 DOF direct-drive parallel manipulator structured as a 2 DOF actuator-redundant parallel cartesian robot with the third DOF by provided by a rotary joint for vertical movement. It is driven by flat coil actuators taken from the read-write heads in hard disk drivers. A photograph and further details are provided in Figure 91. The device is sup-



Specification	
Output Force	100 - 150 gf
Position Resolution	0.020 mm
Static Friction	< 1 gf
Inertia	< 10 g (2DOF), 150 g/cm (3DOF)
Sampling Rate	1 kHz
Workspace	2 cm^3
Interface	Custom board

Figure 91. Pen-Based Force Display (University of Washington)

ported by a real-time controller for PC 486 machines and the resulting force feedback system has been used in a VE testbed to demonstrate the use of force feedback in touching virtual objects. A portable library of basic polygonal objects has been developed, together with models for object interaction. Future goals for this work include the development of a VE composed of 3-D solid objects that can be sensed and manipulated using the force display, and characterizing the mechanical impedance of the human hand, when using the device, as a source of mechanical noise. The researchers are also continuing development of the 2-D component of the device.

The high bandwidth force display is a 2 DOF device intended for use in studying simulated interaction with heavy and stiff virtual objects involving whole-arm motions. Kinematically, this device consists of a simple cartesian mechanism driven by brushless DC motors through steel cable transmission. The user holds a knob mounted on the device endpoint which is decoupled in orientation. A specification for the device is given in Figure 92. This device is supported by a real-time controller for PC 486 machines. Current software can simulate arbitrary environments composed of polygons and circles. Future work with the high bandwidth force display is expected to include the addition of another motion axis and the development of a more compact version of the device with lower static friction.

Specification	
Peak Force	Up to 1200 N
Continuous Force	400 N
Position Resolution	0.015 mm
Sampling Rate	1 kHz
Static Friction	3.5 - 4.0 N
Workspace	3.04 x 4.06 m

Figure 92. High Bandwidth Force Display (University of Washington)

Dr. Hannaford is just starting a new project where University of Washington researchers will work with NASA, Johnson Space Center, scientists in developing a robotic graphics system to support EVA training for astronauts. This work will extend an existing VE already in use for EVA training with force feedback via a 7 DOF robot.