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VIRTUAL ENVIRONMENT TECHNOLOGY FOR TRAINING (VETT)

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III-A-1-c. Haptic Interfaces By J.K. Salisbury and M.A. Srinivasan

The term haptics refers to manual interactions with the environment. In contrast to the purely sensory nature of vision and audition, haptics involves acting on the physical environment as well as sensing it. Haptic interfaces must enable the user to interact with the computer generated virtual environments by receiving motor action commands from the human and by displaying tactual images to the human. An overview of the human haptic system is contained in Appendix 1.

In general, haptic interfaces can be viewed as having two basic functions: (1) to measure the positions and forces (and time derivatives) of the user's hand (and/or other body parts) and (2) to display forces and positions (and/or their spatial and temporal distributions) to the user. Among these position and force variables, the choice of which ones are the command variables (i.e., inputs to the computer) and which are the display variables (i.e., inputs to the human) depends on the hardware and software design, as well as the task the interface is employed to perform.

Consider now an interface that is designed to provide realistic simulations of natural haptic exploration and manipulation. For these tasks, which encompass most of our normal haptic functions, one can imagine a single hardware configuration (an exoskeleton) with all variations effected by changes in software. In such an "ideal" case, the haptic interface would measure positions and display forces. For example, the act of grasping a hammer would be simulated by monitoring the position and posture of the hand and exerting the appropriate forces on the fingers and palm when the fingers and palm are in the appropriate positions. In principle, there would be no need for such a system to measure forces, only to display them. However, force sensing by the interface (in addition to position sensing and force display) is likely to be needed for several reasons. First, even in the situation just described (where reconfigurability is achieved through software changes alone), the presence of noise in the system, as well as the need to compensate for friction and inertia, requires closed-loop force control and hence force sensing. Second, the limitations on available VE technology make it necessary to achieve reconfigurability through changes in hardware as well as software. In other words, a general-purpose VE system will need to augment the exoskeleton with a variety of hardware manipulanda, some of which would include force sensing. Third, in certain applications, it may be desirable to create non-natural environments. For example, in certain cases it might be appropriate to use a fixed-position, force-sensing joystick together with a visual display of tactile information. Alternatively, one might find it helpful to employ a position displaying joystick, with or without force sensing, to present certain kinds of spatial information (e.g., for guiding a passive hand through a maze).

An important set of distinctions concerning haptic interfaces results from consideration of the force display sub-systems in an interface. Broadly speaking, force display systems can be classified as either (1) grounded or (2) ungrounded. Frequently, the distinction between grounding sites is overlooked in the literature. For example, exploration or manipulation of a virtual object requires that force vectors be imposed on the user at multiple regions of contact with the object. Consequently, equal and opposite reaction forces are imposed on the interface. If these forces acting on the interface are self-equilibrating, as in simulating the contact forces that occur when we squeeze an object, then the interface need not be mechanically grounded. However, if the forces are unbalanced, as in pressing a virtual object with a single fingerpad, the equilibrium of the interface requires that it be grounded. For example, we would consider a force reflecting joystick attached to the floor to be a grounded display, whereas a force reflecting exo-skeletal device attached to the user's forearm would be an ungrounded display (it would, in fact, be grounded at the forearm). The grounding choice affects whether or not the user experiences throughout his entire body the stresses induced by contact with a virtual object. The consequences of using an ungrounded display to simulate contact forces which really stem from grounded sources are not known and warrant investigation. A further example of improperly grounded displays occurs with most tactile stimulators. If a tactile stimulator pad is attached to the finger via a strap surrounding the finger, then the net reaction force from the stimulator impinges on the back of the finger (i.e., the system is grounded at the back of the finger). Whether this force can be distributed with a low enough pressure distribution to be imperceptible and whether the absence of stresses throughout the rest of the musculo-skeletal system is inconsequential is not known.

Many of the devices available today have been motivated by needs predating those of virtual environment technology. Simple position/motion measuring systems can be employed to provide command inputs to the computer. These have taken many forms including those that involve contact with the user without force reflection (e.g., simple switches, knobs, joysticks, passive exo-skeletal devices, etc.) and those that measure position/motion without contact (e.g., cameras and other optical and electro-magnetic tracking devices). Applications motivating development of these devices have ranged from the control of equipment (instruments, vehicles, etc.) to biomechanical study of human motion (gait analysis, time and motion studies, etc.). A variety of these devices are discussed in Section III-A-1-b on the Sensing of Body Position and Movement.

The early developments in force displaying haptic interfaces were driven by the needs of the nuclear industry and others for remote manipulation of materials (Johnsen & Corliss, 1971; Vertut 1975; Vertut & Coiffet, 1986; Sheridan 1992). Although the force reflecting teleoperator master arms in these applications were designed to communicate to the operator information about physically real tasks, the recognition of the need for good quality force displays by early researchers (Goertz, 1964; Hill, 1979) continues to be relevant to today's virtual environment applications.

Virtual environment technology is a relatively new field; it draws on a wealth of component technologies for VE haptic interfaces that have been developed for a broad range of non-virtual environment applications under diverse constraints. A rough breakdown of the component technologies that are currently available or being developed in laboratories and companies around the world is as follows:

- Joysticks
- Teleoperator Masters
- Exoskeletal Devices
    - flexible (gloves and suits worn by user)
    - rigid links (jointed linkages affixed to user)
- Tactile displays
    - shape changers
        - shape memory actuators
        - pneumatic actuators
        - micro-mechanical actuators
    - vibrotactile

  - electrotactile
- Non-contact Position Sensors (covered in Section III-A-1-b).

Joysticks are probably the oldest of these technologies and were originally conceived to control aircraft. They may be passive (not force reflecting), as in the joysticks used for cursor positioning, or active (force reflecting), as in many of today's modern flight-control sticks. Even the earliest of control sticks, connected by mechanical wires to the flight surfaces of aircraft, unwittingly presented force information to the pilot reflecting the loads on the flight surfaces. Many of the joysticks available today, force reflecting or not, have been developed for the control of remote manipulators. Generally, these devices employ at most 6 degrees-of-freedom (plus grip control) and have a wide range of performance qualities. A particularly good review of performance characteristics is found in McAffee & Fiorini (1991), and a broad overview of the devices is available in Honeywell (1989). A great deal of work concerning the ergonometrics (shape, switch placement, motion and force characteristics, etc.) has gone into the design of the hand grip of these devices (Brooks & Bejczy, 1985).

Teleoperator Masters have evolved specifically for the control of remote manipulators. These input devices have taken many forms, including joysticks, kinematic replicas, and generalized input devices. Though a reasonably mature technology (in terms of product availability and reliability), these devices tend to be tailored to the manufacturer's slave robot. Teleoperator masters are frequently kinematic replicas of the slave devices they command (a feature which greatly simplifies control algorithms). A number of investigators have adapted teleoperator masters to act as haptic interfaces to virtual environments, but little emphasis has been placed on extending the these masters beyond 7 degrees-of-freedom.

Exoskeletal devices are characterized by the fact that they are designed to fit over and move with the users' limbs or fingers. Because they are kinematically similar to the arm and hands that they monitor and stimulate, they have the advantage of the widest range of unrestricted user motion. As position measuring systems, exoskeletal devices (gloves, suits, etc.) are relatively inexpensive and comfortable to use. However, providing high quality force feedback with such devices is difficult and places great demands on actuator size minimization. The highest performance force reflecting exoskeleton built to date is the Dextrous Teleoperator System Master developed by Sarcos Research Corporation in conjunction with the University of Utah's Center for Engineering Design. Though not inexpensive (approximately $110K), this device utilizes high performance hydraulic actuators to provide a wide dynamic range of force exertion at relatively high bandwidth on a joint-by-joint basis for 7 DOFs up to and including the wrist, with further DOFs in the gripper (Sarcos, 1991).

While the display of net forces is appropriate for coarse object interaction, investigators have also recognized the need for a more detailed display of the haptic interaction at points of contact. In particular, the display of tactile information (force distributions for conveying information on texture and slip), though technically difficult, has long been considered desirable for remote manipulation (Bliss & Hill, 1971). Tactile display systems have also been applied to the needs of the blind, the deaf, and the deaf-blind (Bach-y-Rita, 1982; Reed, Durlach, & Braida, 1982; Reed et al., 1989).

Display systems which attempt to convey information about contact utilize a variety of techniques. Shape changing displays (TiNi, 1990; Rheingold, 1991) convey the local shape of contact by controlled deformation or force exertion across an array of stimulators placed against the skin. Electrotactile and vibrotactile displays stimulate various cutaneous receptors by delivering energy (in the form of electric currents or vibrating mechanical displacement) in an attempt to evoke the sensations of contact (Bliss et al., 1963; Bach-y-Rita, 1982; Kaczmarek et al., 1991). One mode of tactile stimulation which has been relatively unexplored in the development of display systems is that of presenting the relative velocities between the fingers and objects which occur during slip. Conceivably, this could be accomplished by literally placing a moving surface (rotating a small ball, for example) under the fingertips. By careful control of the ball's motion and vibration, a variety of tactile sensations could be elicited.

The emerging field of micro-mechanical systems holds promise for providing very fine arrays of tactile stimulators. Arrays of surface-normal, electrostatic actuators currently being developed for sensors could be adapted for use in high-resolution tactile displays (Trimmer, Gabriel & Mahadevan, 1987). Micromachined diaphragm pressure sensors can be redesigned with concentric membranes suspended over connected chambers to form electrostatic-pneumatic actuators for use in sensors and as surface-normal actuators. Although capable of relatively small forces and deflections, arrays of such actuators integrated with addressing electronics would be inexpensive, light-weight, and compact enough to be worn without significantly impeding hand movement or function. In addition, the current technology makes feasible a 20 x 20 array of individually controlled stimulators on a 1 cm x 1 cm chip. Finally, recent work on thin-film, shape-memory alloys would enhance the attractiveness of shape-changing displays by increasing stimulator densities and actuation bandwidths.

Table III-4 outlines the operational characteristics of some current haptic interface components.

TABLE III-4. HAPTIC INTERFACES

EXO-SKELETAL AND GLOVE DEVICES

SOURCE	DEVICE	DESCRIPTION	POSITION SENSING	FORCE DISPLAY	TACTILE DISPLAY	NOTES
EXOS	Dextrous Hand Master	hand exo-skel	finger motions via hall effect .5 degree resolution 20 DOF			$15K incl. interfaces and software for PC/AT
	Grip-Master	wrist exo-skel	2 wrist motions via hall effect	force measurement at up to 5 sites on fingers		$9950 raw data version. incl. interfaces and software for PC/AT $20,000 calibrated version above plus devices and software for calibrating force and angle
	Exoskeletal Arm Master	arm exo-skel	arm motions via pots			lightweight device for tracking elbow and shoulder and wrist pronation/supination. (Under development)
	Safire	finger	fingers via hall effect	finger torques via electric motors, wrist grounded		Under development.

All measurements made in EXOS products are made with hall effect transducers with < .1 degree resolution. Resolutions above are effective resolutions measurement of human joint positions.

Contact: EXOS, Inc.
8 Blanchard Rd
Burlington MA 01803
(617) 229-2075

TABLE III-4. HAPTIC INTERFACES

EXO-SKELETAL AND GLOVE DEVICES (Continued)

SOURCE	DEVICE	DESCRIPTION	POSITION SENSING	FORCE DISPLAY	TACTILE DISPLAY	NOTES
VPL	Data Glove	glove	fingers fiber optic 10 sensors 1 degree resolution			$8,800
	data suit	body suit	body and limbs fiber optic 50 sensors 1 degree resolution			$90k-$120k Contact: VPL Research 656 Bair Island Road Redwood City, CA 94603 (415) 361-1710
Virtex	CyberGlove	glove	fingers strain gauges 18 sensors .5 degree resolution			$6500
	CyberForce (under development)	glove w/ grip force feedback	fingers strain gauges	grip force feedback		(under development) Contact: Jim Kramer Virtex Corp. P.O. Box 5984 Stanford CA 94309 (415) 497-1204

TABLE III-4. HAPTIC INTERFACES

TELEOPERATOR MASTERS

SOURCE	DEVICE	DESCRIPTION	POSITION SENSING	FORCE DISPLAY	TACTILE DISPLAY	NOTES
French Atomic Energy Commission (CEA)	MA-23	teleoperator master electric	6-DOF	net force at handgrip, earth grounded		Electric motors, cable transmissions, full master-slave systems, $100K-$250K Force: 20-60+ lbf. Contact: SNE la Calhene 1, Rue Du Petit-Clamart 78140 Vellizy-Villacoublay FRANCE (1) 46.30.66.00
Argonne National Labs	"ARM"	teleopertaor master, electric	6-DOF+gripper	net force at handgrip, earth grounded		availability unknown force: 10-40 Lbs. Contact: Argonne National Lab.
Sarcos Res. Corp/ U. Utah	Dextrous Arm Master	teleoperator master hydraulic	7-DOF + gripper	net force at handgrip, earth grounded		Dextrous ARM and Controller, $111,000 Position and Force Resolution: 12 bits Maximum force 5 - 10 lbf Small Displacement Bandwidth: 100 Hz Peak Velocities: 800 deg/sec at shoulder, faster at distal joints Acceleration: up to 20G's. Actuation: 3000psi hydraulic (other options available, improved versions under development)
	DHM Version II	passive hand master, exo-skel	20-DOF finger motions via hall effect sensors			(on request) Contact: Sarcos Research Corp. 261 East 300 South, Suite 150 Salt Lake City, UT 84111 (801) 531-0315

TABLE III-4. HAPTIC INTERFACES

TELEOPERATOR MASTERS (Continued)

SOURCE DEVICE	DESCRIPTION	POSITION SENSING	FORCE DISPLAY	TACTILE DISPLAY	NOTES
Shilling Omega	teleoperator mini-master electric	6-DOF arm	net force at handgrip, earth grounded		DC torque motors acting through harmonic reducers. 6 DOF + grip. 12-40 in-lb max on joints, 2 lbf grip force. Backdrive friction low but not measured. Position Resolution: 16 bits/360 degrees at joints. Contact: Shilling Development, Inc. 1633 da Vinci Ct. Davis CA 95616 (916) 753-6718

TABLE III-4. HAPTIC INTERFACES

JOYSTICKS

SOURCE	DEVICE	DESCRIPTION	POSITION SENSING	FORCE DISPLAY	TACTILE DISPLAY	NOTES
Tele-Technologies	TT-2000 Force Reflecting Hand Controller	generalized teleoperator master, joystick	6-DOF	net force earth grounded		Electric motors, cable transmission. Resolution: <.028 deg on all axes Max force: > 34 N at handgrip, Friction Torque: .06 to .9Nm. Price: $30K-$50K. Contact: Douglas McAffee TeleTechnologies 1621 Bardale Ave San Pedro, CA 90371 (213) 832-3218
ATT	(joystick)	2-DOF mini-joystick	2-DOF	2-DOF force vector, high bandwidth		(under development) force and position display modes: position bandwidth > 200Hz for small displacements position resolution 3000 counts, control to +/- 2 counts force resolution 12bits, 75gms max force bandwidth > 200HZ for solid contact Contact: Brian Schmalt AT&T Bell Labs. Holmdel, NJ 07733 (908) 949-3260
Measurement Systems Inc.	(various)	2/3 DOF joysticks	position sensing of passive stick	(some sense force, but don't display it)		Contact: Measurement Systems Inc.

TABLE III-4. HAPTIC INTERFACES

TACTILE DISPLAYS

SOURCE	DEVICE	DESCRIPTION	POSITION SENSING	FORCE DISPLAY	TACTILE DISPLAY	NOTES
Begej Corp.	tactile stimulator	fingertip and tool-mounted tactile arrays			vibrotactile or shape changer, 37 cell finger display, 128 cell tool display	Stimulator cells: 3mm diam. x 2mm thick, center-center spacing 3mm. Pulse width modulated at 10hz, with 10ms element response. 35 psi system. Contact: Begej Corp. 5 Claret Ash Road Little, CO 80127 (303) 932-2186
EXOS	touch master				finger stim.	Voice coil vibrator for finger tip, Variable amplitude & frequency. Price: about $2K per stimulator. Contact: Exos, Inc. (see above)
TiNi Corp	tactors	shape-memory alloy tactile stimulators, points and arrays			shape changer true dc response	Notes: Arrays of up to 30 tactors down to .120" center-center distance. Monitor & 3x3 tactile display, $7000. Contact: TiNi Alloy Co. 1144 65th Street, Unit A Oakland, CA 94608 (415) 658-3172

TABLE III-4. HAPTIC INTERFACES

TACTILE DISPLAYS (Continued)

SOURCE	DEVICE	DESCRIPTION	POSITION SENSING	FORCE DISPLAY	TACTILE DISPLAY	NOTES
Tele Sensory Systems	Opticon	tactile display for blind reading			vibrotactile	20x5 pins on 1.5" x .75" area, DC to 250Hz response, $3495. TeleSensory Systems N. Bernardo Ave. Mtn. View CA (800 227-8418 (415) 960-0920 Rob Savoy, VP x212
Air-muscle (UK)	Teletact				shape changer tactile array pneumatic	VPL Research (see above) to be exclusive US distributor. 24 cell device integrated with DataGlove to be released in near future for approximately $30K-$40K. "High bandwidth" for texture simulation claimed.