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HAPTIC INTERFACES: HARDWARE, SOFTWARE AND HUMAN PERFORMANCE¹

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ABSTRACT

Virtual environments are computer-generated synthetic environments with which a human user can interact to perform a wide variety of perceptual and motor tasks. At present, most of the virtual environment systems engage only the visual and auditory senses, and not the haptic sensorimotor system that conveys the sense of touch and feel of objects in the environment. Computer keyboards, mice and trackballs constitute relatively simple haptic interfaces. Gloves and exoskeletons that track hand postures have more interaction capabilities and are available in the market. Although desktop and wearable force-reflecting devices have been built and implemented in research laboratories, the current capabilities of such devices are quite limited. To realize the full promise of virtual environments and teleoperation of remote systems, further developments of haptic interfaces are critical.

In this paper, the status and research needs in human haptics, technology development and interactions between the two are described. In particular, the excellent performance characteristics of Phantom, a haptic interface recently developed at MIT, are highlighted. Realistic sensations of single point of contact interactions with objects of variable geometry (e.g., smooth, textured, polyhedral) and material properties (e.g., friction, impedance) in the context of a variety of tasks (e.g., needle biopsy, switch panels) achieved through this device are described and the associated issues in haptic rendering are discussed.

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APPLICATIONS OF SYNTHETIC ENVIRONMENTS (SE)

Synthetic environments (SE), which include both virtual environments (VE) and teleoperation, have generated considerable excitement, owing to the wide variety of applications in which they can play a significant role (listed below; Ref. 1). At present, most of the VE systems engage only the visual and auditory senses, and not the haptic sensorimotor system that conveys the sense of touch and feel of objects in the environment. Manual interactions with SE are important in sensorimotor tasks such as training of surgeons with VE or conveying the feel of an object to the participants of a teleconference. They may also play a significant role in cognitive tasks such as memorization and analysis of multidimensional databases or teaching the implications of the violations of physical laws.

- **Design, Manufacturing, and Marketing**
- **Medicine and Health Care**
- **Teleoperation for Hazardous Operations**
- **Training**
- **Education**
- **Entertainment**
- **Information Visualization**
- **Telecommunications**

Manual interaction with SE is important in particular tasks within each application area.

Figure 1

HAPTICS: MANUAL INTERACTIONS WITH THE ENVIRONMENT - FOR EXPLORATION OR MANIPULATION

The term Haptics refers to manual interactions with real or virtual environments. It includes both exploration of objects to obtain information about the environment and manipulation of objects to alter the environment. In contrast to the purely sensory nature of vision and audition, the human haptic system involves tight integration of both sensory and motor components. Further, the sensory information can be divided into two classes: (1) tactile information, referring to the sense of contact with the object, mediated by the responses of low-threshold mechanoreceptors innervating the skin (say, the finger pad) within and around the contact region; and (2) kinesthetic information, referring to the sense of position and motion of limbs along with the associated forces, conveyed by the sensory receptors in the skin around the joints, joint capsules, tendons, and muscles, together with neural signals derived from motor commands.

Haptics: Manual interactions with the environment - for exploration or manipulation

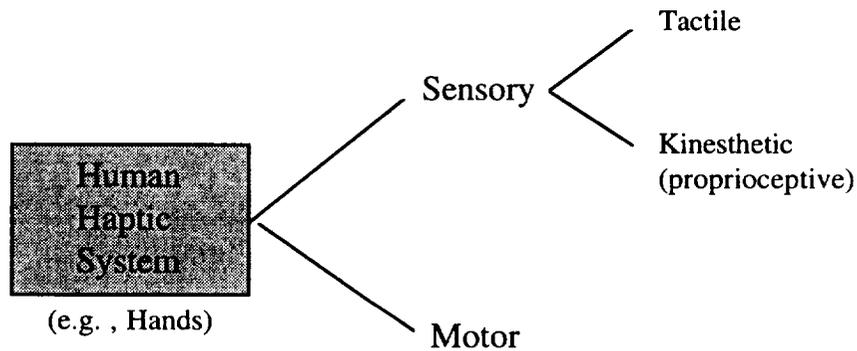


Figure 2

HAPTIC INTERFACES

Haptic interfaces are devices that enable manual interaction with virtual environments or teleoperated remote systems. They are employed for tasks that are usually performed using hands in the real world, such as manual exploration and manipulation of objects. In general, they receive motor action commands from the human user and display appropriate tactual images to the human. The command and display variables are listed below.

Haptic Interfaces

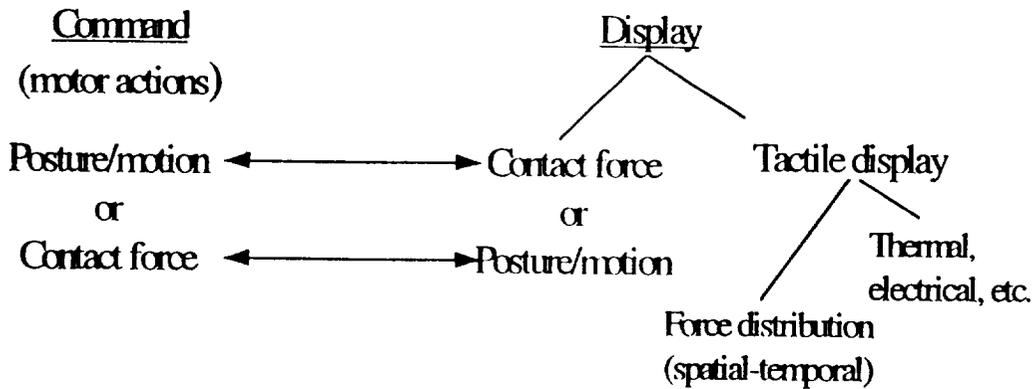
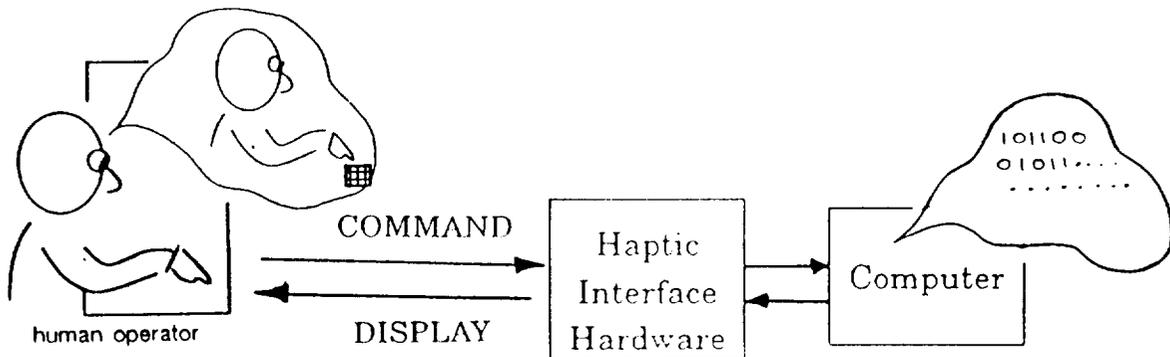


Figure 3

CLASSIFICATION OF HAPTIC INTERFACES

Haptic interfaces can be classified in several ways. First, classification is based on whether they are force-reflecting or not, as well as by what types of motions (e.g., how many degrees of freedom) and contact forces they are capable of simulating. The second type of classification is based on whether they are simulating the touch, feel, and manipulation of objects directly in contact with the skin or through a tool. A third set of important distinctions are based on whether the force display systems are ground-based, such as joysticks and other hand controllers, or body-based, such as gloves and exoskeletons.

- 1. Based on motions and/or forces (e.g., presence or absence of force reflection, degrees of freedom, types of forces)**
- 2. Ideal exoskeleton or tool handle approach**
- 3. Ground-based or body-based**

Figure 4

AVAILABLE HAPTIC INTERFACES

A variety of haptic interfaces are currently available. Computer keyboards, mice and trackballs constitute relatively simple haptic interfaces. Gloves and exoskeletons that track hand postures have more interaction capabilities and are available in the market. Although desktop and wearable force-reflecting devices have been built and implemented in research laboratories, the current capabilities of such devices are quite limited. There exist a number of examples of tactile stimulators for the finger, including pneumatic shape changers, electrocutaneous stimulators, and vibrating arrays, but none provides convincing tactile images and all are awkward to use (Ref. 2).

- **Position sensors**
- **Joysticks**
- **Point-interaction robotic devices**
- **Teleoperator masters**
- **Exoskeletal devices:**
 - **flexible (gloves and suit worn by user)**
 - **rigid links (joined linkages affixed to user)**
- **Tactile displays:**
 - **shape changers (shape memory actuators, pneumatic actuators, micro-mechanical actuators)**
 - **vibrotactile**
 - **electrotactile**

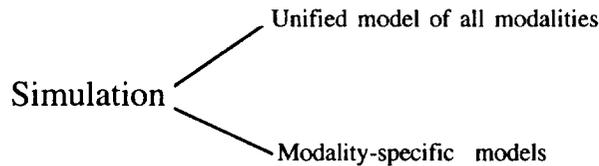
Figure 5

SOFTWARE FOR HAPTIC INTERACTIONS

Similar to the software needed to generate visual images, the software necessary to generate tactual images can be classified into three major groups: haptic interaction software, simulation of object behavior, and software for rendering tactual images. Haptic interaction software mainly consists of reading the state of the haptic interface device. Simulation of object behavior requires physical models of virtual objects. This can be accomplished either by a unified model for all the modalities (e.g., visual, haptic, acoustic) or through separate models for each modality, together with correlation algorithms for consistency among the displays corresponding to each of the modalities. The software for rendering the tactual images receives the output of the physical model and generates the commands needed to drive and control the interface device.

Software for Haptic Interactions

Device State - Reading and interpreting the state of the haptic devices.



Rendering - Control of haptic display

Figure 6

THE PHANTOM

The Phantom is a force-reflecting haptic interface recently developed at MIT (Ref. 3). It is capable of generating realistic sensations of single point contact interactions. It is essentially a robot with six degrees of freedom, capable of generating a three-dimensional force vector at its end effector, which can either be a thimble or a stylus that is manipulated by the human user.

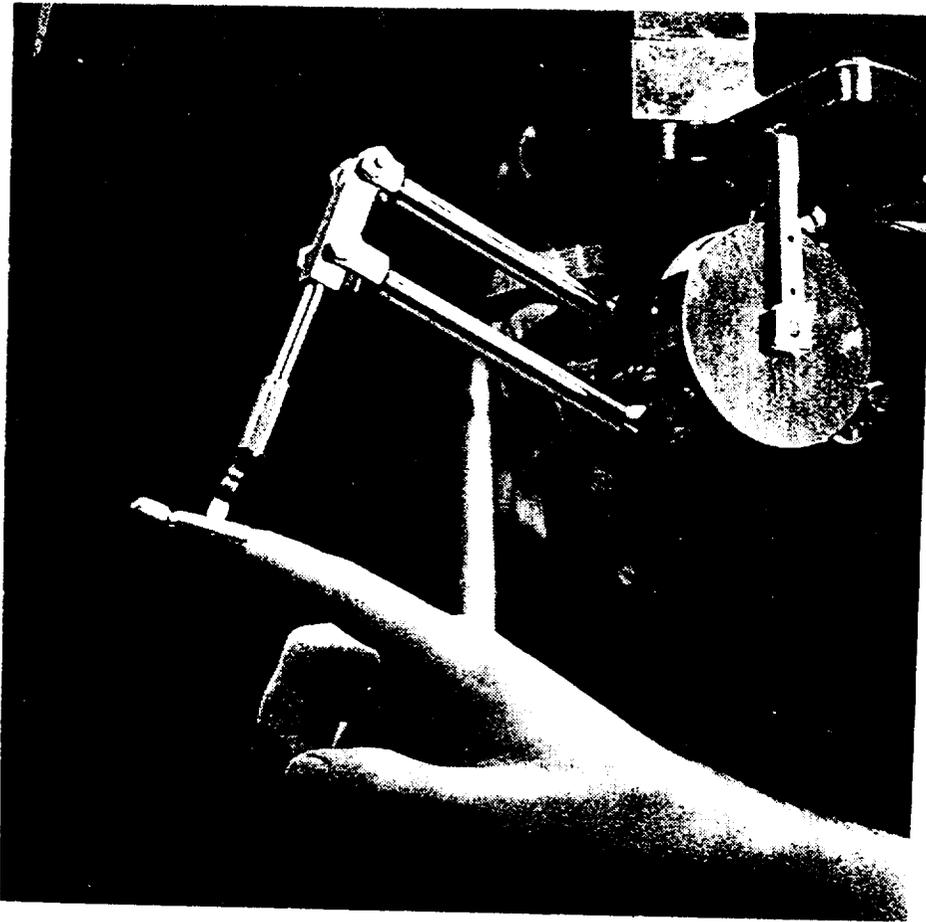
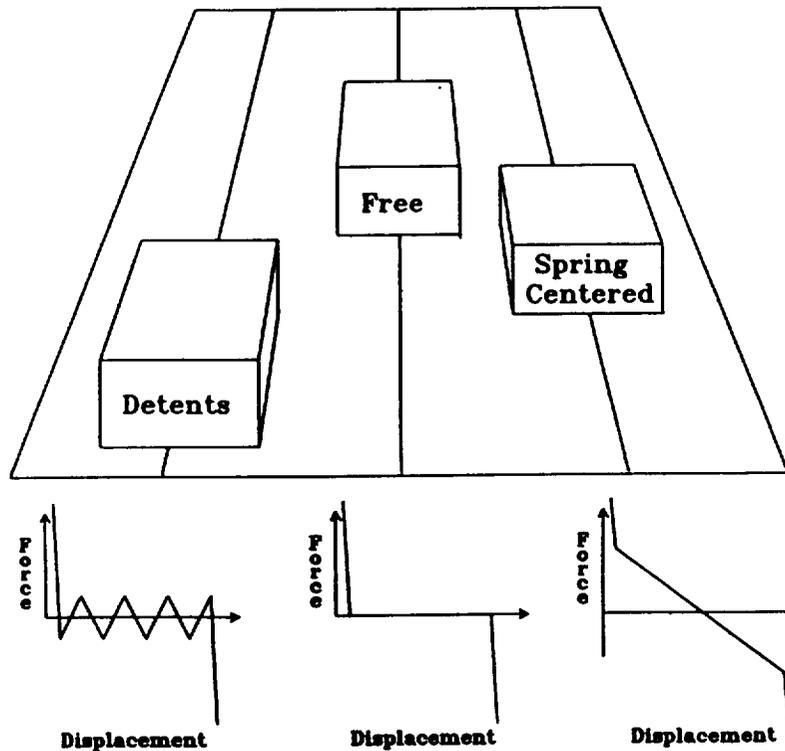


Figure 7

SLIDER SWITCHES

A variety of touch interactions have been haptically rendered using the Phantom (Ref. 4). Shown below are three types of slider switches and their respective force-displacement behavior. In addition to the properties of mass, viscosity, stiction, and surface stiffness, each cube has an underlying characteristic spring function.

Slider Switches



In addition to the properties of mass, viscosity, stiction, and surface stiffness, each cube has an underlying characteristic spring function.

Figure 8

BUTTONS WHICH "CLICK"

The feel of push buttons which "click" has also been displayed through the Phantom to the human user. Each of the buttons shown below simulate the force-displacement relationship shown schematically, but feel distinct owing to differences in the values of parameters such as stiffness.

Buttons which "Click"

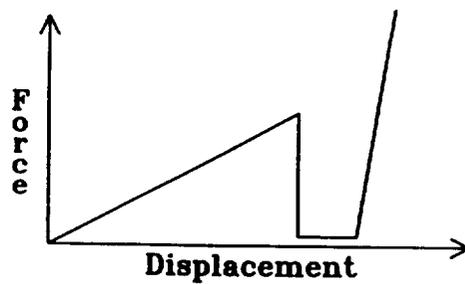
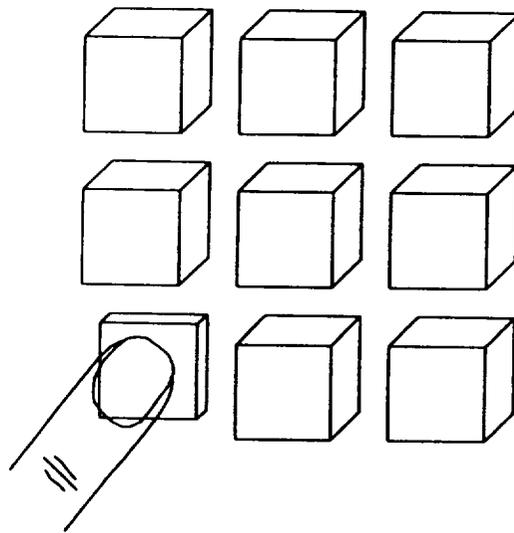
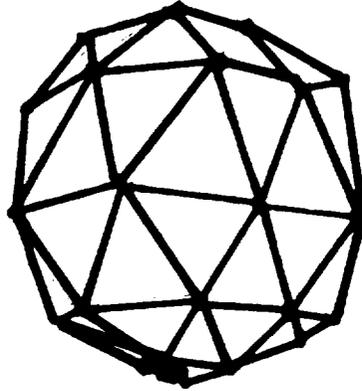


Figure 9

RENDER: RENDERS POLYGONAL SURFACES

The haptic display of arbitrarily shaped objects represented as polyhedra has been achieved with the Phantom. The rendering software uses standard graphics file formats and is capable of simulating both convex and concave surfaces.



- **Allows haptic display of arbitrarily shaped objects**
- **Uses standard graphics file formats**
- **Convex and concave**
- **Can render arbitrarily thin objects**

Figure 10

Two Phantoms have been used together to allow a user to perform two-fingered manipulation of virtual objects as shown below. Such contact interactions are analogous to the use of tools in real environments.

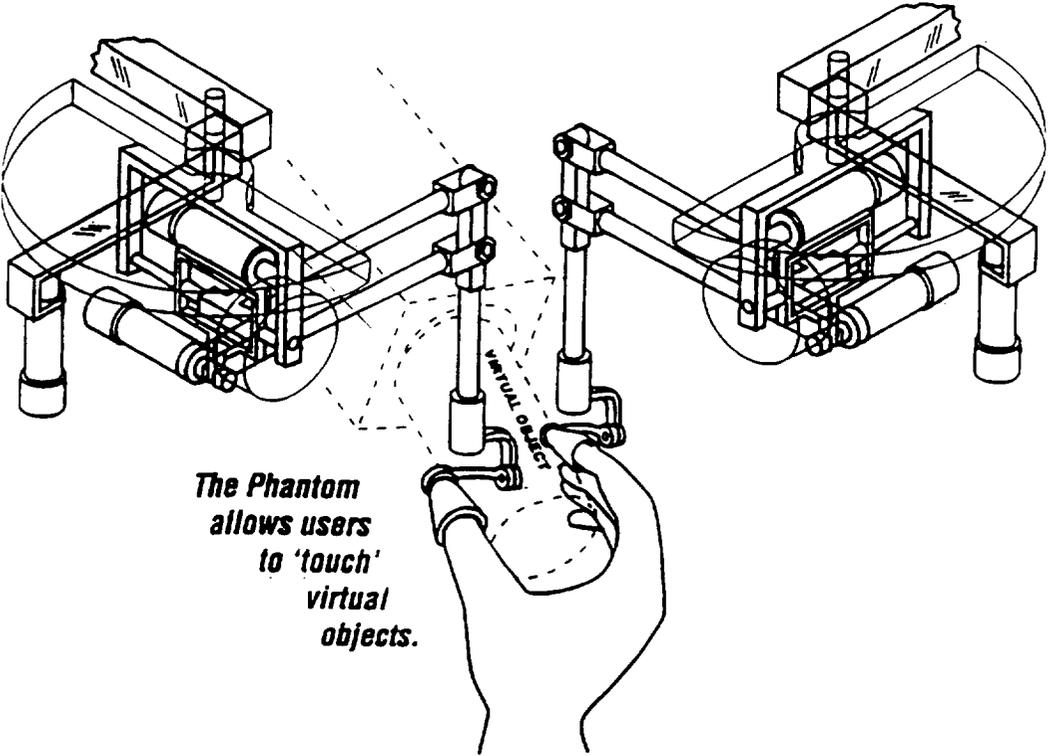
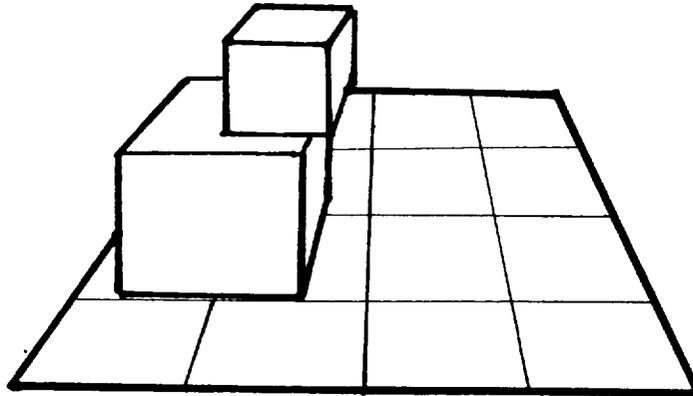


Figure 11

BLOCKS: DYNAMIC SIMULATION OF BLOCKS IN 3D

Using two Phantoms, the dynamic simulation of 3D blocks being manipulated by a user has been achieved. Both visual and haptic displays were provided to the user.



- **Two hand/finger manipulation**
- **Static friction model**
Phantom and walls, Phantom and blocks,
blocks and blocks
- **Gravity**

Figure 12

WHAT ARE ELEMENTS OF HAPTIC INTERACTION?

Listed below is a summary of the elements of haptic interactions.

- **Sensed elements:**
 - Motion, force, tactile, temperature, heat flow, current flow, pain, etc.**
- **Perceived events and states:**
 - Impact**
 - Sustained contact**
 - Slip**
 - Friction, texture**
 - Freedom/constraint in motion**
 - Compliance**
 - Curvature**
- **Workless interactions:**
 - Imposing and detecting constraint**
- **Work interactions:**
 - Force over distance, impulse, momentum and energy**

Figure 13

WHAT WE HAVE DONE

The status of the work done at the MIT AI Laboratory is given below:

- **Developed class of haptic interface permitting force vector display - Phantom**
- **Demonstrated basic interaction elements**
impact and constraint forces
object shape, motion
friction, texture
surface and object, impedance
- **Combined basic elements to build simple mechanical worlds:**
astroid, blocks,
needle-biopsy, switch panels
- **Developed rendering algorithms for polyhedral objects**
- **Begun development of rendering algorithms for visco-elastic materials**

Figure 14

HUMAN HAPTIC PERFORMANCE

A basic understanding of the biomechanical, sensorimotor, and cognitive abilities of the human haptic system is essential for further improvements in the design of hardware and software of haptic interfaces. Summarized below are some of the quantitative data (Refs. 2 and 5) on human haptic performance which set some of the design specifications of interface devices.

Tactile Sensory System:

**Vibrations - detectable up to 1khz
thresholds - 0.3 to 30 microns
Spatial resolution - 1mm at fingerpad**

Kinesthetic Sensory System:

**Just noticeable differences (JND) for joint
angles ~ 1 to 3 degrees**

Motor System:

Bandwidths: 1 to 10 Hz

Active Touch with All Three Systems

**JNDs for two-fingered pinch grasp:
Length ~ 10% or less
Force ~ 7%
Compliance ~ 8%
Viscosity ~ 14%
Mass ~ 21%**

Figure 15

RESEARCH NEEDS

A comprehensive program to develop a variety of haptic interfaces for virtual environments and teleoperation needs to include research in the areas shown below. Since progress in the three areas is interdependent, the desirable course of development for a challenging application is to continually build improved versions of haptic devices based on experimental data obtained from the previous versions on the performance of humans, devices and the interaction between the two.

- **Human Haptics**
 - Biomechanics**
 - Psychophysics**
- **Hardware**
 - Position trackers**
 - Force displays**
 - Tactile displays**
- **Software**
 - Multimodal interactions**
 - Real time simulations**
- **Matching Human and Device Performance**
 - Comfort**
 - Simulation methods**
 - Evaluation**

Figure 16

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