

What is Haptics?

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1. Introduction

Haptics refers to sensing and manipulation through touch. Since the early part of twentieth century, the term haptics has been used by psychologists for studies on the active touch of real objects by humans. In the late nineteen-eighties, when we started working on novel machines pertaining to touch, it became apparent that a new discipline was emerging that needed a name. Rather than concocting a new term, we chose to redefine haptics by enlarging its scope to include machine touch and human-machine touch interactions. Our working definition of haptics includes all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two; and the environments can be real, virtual or teleoperated. This is the sense in which substantial research and development in haptics is being pursued around the world today..

In order to organize the rapidly increasing multidisciplinary research literature, it is useful to define sub-areas of haptics. Haptics can be subdivided into three areas

1. human haptics - the study of human sensing and manipulation through touch,
2. machine haptics – the design, construction, and use of machines to replace or augment human touch.
3. computer haptics -algorithms and software associated with generating and rendering the touch and feel of virtual objects (analogous to computer graphics).

Consequently, multiple disciplines such as biomechanics, neuroscience, psychophysics, robot design and control, mathematical modeling and simulation, and software engineering converge to support haptics. Wide varieties of applications have emerged and span many areas of human needs such as product design, medical trainers, and rehabilitation.

Haptics is poised for rapid growth. Just as the primitive man forged hand tools to triumph over harsh nature, we need to develop smart devices to interface with information-rich real and virtual worlds. Given the ever-increasing quantities and types of information that surrounds us, and to which we need to respond rapidly, there is a critical need to explore new ways to interact with information. In order to be efficient in this interaction, it is essential that we utilize all of our sensorimotor capabilities. Our haptic system – with its tactile, kinesthetic, and motor capabilities together with the associated cognitive processes – presents a uniquely bi-directional information channel to our brains, yet it remains underutilized. If we add force and/or distributed tactile feedback of sufficient range,

resolution and frequency bandwidth to match the capabilities of our hands and other body parts, a large number of applications open up, such as haptic aids for a blind user surfing the net or a surgical trainee perfecting his trade. Ongoing engineering revolutions in information technology and the miniaturization of sensors and actuators are bringing this dream ever closer to reality.

Virtual environments (VEs), generally referred to as virtual reality in the popular press, have caught the imagination of lay public as well as researchers working in a wide variety of disciplines. VEs are computer-generated synthetic environments with which a human user can interact to perform perceptual and motor tasks. A typical VE system consists of a helmet that can project computer-generated visual images and sounds appropriate to the gaze direction, and special gloves with which one can command a computer through hand gestures. The possibility that by wearing such devices, one could be mentally transported to and immersed in virtual worlds built solely through software is both fascinating and powerful. Applications of this technology include a large variety of human activities such as training, education, entertainment, health care, scientific visualization, telecommunication, design, manufacturing and marketing.

Virtual environment systems that engage only the visual and auditory senses of the user are limited in their capability to interact with the user. As in our interactions with the real world, engaging the haptic sensorimotor system that not only conveys the sense of touch and feel of objects, but also allows us to manipulate them, is desirable. In particular, the human hand is a versatile organ that is able to press, grasp, squeeze or stroke objects; it can explore object properties such as surface texture, shape and softness; it can manipulate tools such as a pen or a jack-hammer. Being able to touch, feel, and manipulate objects in an environment, in addition to seeing (and/or hearing) them, gives a sense of compelling immersion in the environment that is otherwise not possible. Real or virtual environments that deprive the human user of the touch and feel of objects seem deficient and seriously handicap human interaction capabilities. It is likely that a more immersive experience in a VE can be achieved by the synchronous operation of even a simple haptic interface with a visual and auditory display, rather than by large improvements in, say, the fidelity of the visual display alone.

Haptic interfaces are devices that enable manual interactions 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 user. Such haptic interactions may or may not be accompanied by the stimulation of other sensory modalities such as vision and audition.

Although computer keyboards, mice, trackballs, and even instrumented gloves available in the market can be thought of as relatively simple haptic interfaces, they can only convey the user's commands to the computer, and are unable to give a natural sense of touch and feel to the user. Recent advances in the development of force-reflecting haptic interface

hardware as well as haptic rendering software have caused considerable excitement. The underlying technology is becoming mature and has opened up novel and interesting research areas. However, to really enable the wide variety of known applications of haptics, and even more so, the applications that we cannot yet imagine, it is critical to understand the nature of touch interaction - how and what do we perceive, how do we manipulate, and how are these related to task performance. The challenge of haptics research then is two-fold: to gain a deep scientific understanding of our haptic sensorimotor system and to develop appropriate haptic interface technology.

In this short introductory document, we primarily provide an overview of the major sub-areas of haptics and refer the reader to some of our more detailed reviews (which, in turn, have substantial references to works by us and others) for a more in-depth look. In the first section, we provide the basics of how we feel and how to mimic that feel. The following section is a basic introduction to *human haptics*, the study of the human sensorimotor system relevant to manual exploration and manipulation. The subsequent section is on *machine haptics*, concerned with the electromechanical devices used as haptic interfaces. Next, the emerging field of *Computer Haptics* is defined and references to review papers that deal with the paradigms, algorithms, and software for haptic interactions are provided.. Several exciting applications of haptics, such as the development of medical simulators for training and virtual environments shared by multiple users, are described. Finally, future challenges and opportunities in haptics are briefly covered..

2. Touching Real and Virtual Objects

When a human user touches a real object directly or through a tool, forces are imposed on the user's skin. The associated sensory information, mediated by sensors in the skin, joints, tendons and muscles, is conveyed to the brain by the nervous system and leads to haptic perception. The subsequent motor commands issued by the brain activate the muscles and result in, say, hand and arm motion that modifies the touch sensory information. This sensorimotor loop continues to occur during both exploration and manipulation of objects.

In order to create the sensation of touching virtual objects, we need to generate the reaction force of objects applied on the skin. Touching a real object through a tool is mimicked by the use of a force reflecting haptic interface device. When the human user manipulates the end-effector of the haptic interface device, the position sensors on the device convey its tip position to the computer. The models of objects in the computer calculate in real-time the torque commands to the actuators on the haptic interface, so that appropriate reaction forces are applied on the user, leading to haptic perception of virtual objects.

3. Human Haptics

In order to develop haptic interfaces that are designed for optimal interactions with the human user, it is necessary to understand the roles played by the mechanical, sensory, motor and cognitive subsystems of the human haptic system. The mechanical structure of the human hand consists of an intricate arrangement of 19 bones connected by almost as many frictionless joints, and covered by soft tissues and skin. The bones are attached to approximately 40 intrinsic and extrinsic muscles through numerous tendons which serve to activate 22 degrees of freedom of the hand. The sensory system includes large numbers of various classes of receptors and nerve endings in the skin, joints, tendons, and muscles. Appropriate mechanical, thermal or chemical stimuli activate these receptors, causing them to transmit electrical impulses via the afferent neural network to the central nervous system (of which the brain forms a part), which in turn sends commands through the efferent neurons to the muscles for desired motor action.

In any task involving physical contact with an object, be it for exploration or manipulation, the surface and volumetric physical properties of the skin and subcutaneous tissues play important roles in its successful performance. For example, the fingerpad, which is used by primates in almost all precision tasks, consists of ridged skin (about 1 mm thick) that encloses soft tissues composed of mostly fat in a semi-liquid state. As a block of material, the fingerpad exhibits complex mechanical behaviour -- inhomogeneity, anisotropy, rate and time-dependence. The compliance and frictional properties of the skin together with the sensory and motor capabilities of the hand enable gliding over a surface to be explored without losing contact, as well as stably grasping smooth objects to be manipulated. The mechanical loading on the skin, the transmission of the mechanical signals through the skin, and their transduction by the cutaneous mechanoreceptors are all strongly dependent on the mechanical properties of the skin and subcutaneous tissues.

Tactual sensory information conveyed to the brain from the hand in contact with an object can be divided into two classes:

- (i) *tactile information*, referring to the sense of the nature of contact with the object, mediated by the responses of low threshold mechanoreceptors innervating the skin (say, the fingerpad) within and around the contact region;
- (ii) *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.

Only tactile information is conveyed when objects are made to contact a passive, stationary hand, except for the ever-present kinesthetic information about the limb posture. Only kinesthetic information is conveyed during active, free (i.e., no contact with any object or other regions of skin) motion of the hand, although the absence of tactile information by itself conveys that the motion is free. Even when the two extreme cases mentioned above are included, it is clear that *all* sensory and manipulatory tasks performed actively with the normal hand involve both classes of information. In addition, free nerve endings and

specialized receptors which signal skin temperature, mechanical and thermal pain, as well as chemogenic pain and itch are also present.

The control of contact conditions is as important as sensing those conditions for the successful performance of any task. In humans, such control action can range from a fast muscle or spinal reflex to a relatively slow conscious deliberate action. Experiments involving lifting of objects held in a pinch grasp show that motor actions such as increasing grip force are initiated as rapidly as within 70 msec. after an object begins to slip relative to the fingerpad, and that the sensory signals from the cutaneous afferents are critical for task performance. Clearly, the mechanical properties of skin and subcutaneous tissues, the rich sensory information provided by a wide variety of sensors that monitor the tasks continuously, and the coupling of this information with the actions of the motor system are responsible for the human abilities of grasping and manipulation. A brief summary of the psychophysical and neurophysiological results available on the human haptic abilities in real environments and the references to the corresponding literature is given in [3] and [7].

4. Machine Haptics

Machine haptics refers to the design, construction, and use of machines to replace or augment human touch; although such machines include autonomous or teleoperated robots, here we focus on haptic interfaces to VEs. Haptic interfaces are devices composed of mechanical components in physical contact with the human body for the purpose of exchanging information with the human nervous system. In performing tasks with a haptic interface, the human user conveys desired motor actions by physically manipulating the interface, which, in turn, displays tactual sensory information to the user by appropriately stimulating his or her tactile and kinesthetic sensory systems. Thus, in general, haptic interfaces can be viewed as having two basic functions: (1) to measure the positions and contact forces (and time derivatives) of the user's hand (and/or other body parts) and (2) to display contact forces and positions (and/or their spatial and temporal distributions) to the user. Among these position (or, kinematic) and contact force variables, the choice of which ones are the motor action variables (i.e., inputs to the computer) and which are the sensory display variables (i.e., inputs to the human) depends on the hardware and software design, as well as the tasks the interface is employed for. At present, most of the force-reflecting haptic interfaces sense position of their end-effector and display forces to the human user.

Ultimately, human abilities and limitations set the performance specifications of haptic devices. Simulation of haptic interactions with VEs that are designed to mimic real environments will always be approximate, and the limits of human performance will determine which approximations are sufficient. The desirable features of force-reflecting haptic interfaces are as follows:

1. Low back-drive inertia and friction, and no constraints on motion imposed by the device kinematics, so that free motion feels free.
2. The range, resolution, and bandwidth, both in terms of position sensing and force reflection, should match those of the human for the tasks for which the haptic interface is employed. The user (a) should not be able to go through rigid objects by exceeding the force range of the interface, (b) should not be able to feel unintended vibrations such as those due to quantization of position or a low servo rate, and (c) should not feel stiff objects as soft due to low structural and servo stiffness. These conditions are difficult to satisfy because of the fine sensitivity and ~ 1 kHz bandwidth of the human tactile system, but the fact that the human control bandwidth in haptic interactions is only on the order of 10Hz is helpful.
3. Ergonomics and comfort: Making the human user comfortable when wearing or manipulating a haptic interfaces is of paramount importance, since pain, or even discomfort, supersedes all other sensations.

A survey of the haptic interface devices developed so far is beyond the scope of this paper, but can be found in [1], [3] and [7]. In our MIT Touch Lab, for example, we have developed device hardware, interaction software and psychophysical experiments pertaining to haptic interactions with virtual environments. Two specialized devices for performing psychophysical experiments, the linear and planar graspers, have been developed. The linear grasper is capable of simulating fundamental mechanical properties of objects such as compliance, viscosity and mass during haptic interactions. Virtual walls and corners were simulated using the planar grasper, in addition to the simulation of two springs within its workspace. The PHANTOM® device, another haptic display device originally developed at MIT [5], has been used to prototype a wide range of force-based haptic display primitives. A variety of haptic rendering algorithms for displaying the shape, compliance, texture, and friction of solid surfaces have been implemented on the PHANTOM ([4], [5], [8] and [9]). All the three devices – the linear and planar graspers and the PHANTOM - have been used to perform psychophysical experiments aimed at characterizing the sensorimotor abilities of the human user and the effectiveness of computationally efficient rendering algorithms in conveying the desired object properties to the human user.

4. Computer Haptics

Computer Haptics is a rapidly emerging area of research that is concerned with the techniques and processes associated with generating and displaying the touch and feel of virtual objects to a human operator through a force reflecting device. Analogous to computer graphics, it deals with models and behavior of virtual objects together with rendering algorithms for real-time display. It includes the software architecture needed not

only for haptic interactions but also their synchronization with visual and other display modalities.

The basic process of haptically rendering objects in virtual environments with a force-feedback device is as follows. Typically, a haptic rendering algorithm is made of two parts: (a) collision detection and (b) collision response. As the user manipulates the generic probe of the haptic device, the new position and orientation of the probe is sensed by the sensors in the device. If no collision between the simulated avatar of the probe and virtual objects are detected, the haptic interface device remains passive and no forces are reflected back to the user. If the probe is detected to have collided with the object, the mechanistic model calculates the reaction force based on the penetration depth of the probe into the virtual object. The calculated force vectors may then be modified by appropriately mapping them over the object surface to take into account the surface details. The modified force vectors are then fed back to the user through the haptic device. This sequence of collision detection and response is termed a haptic loop, which needs to continuously run at around 1 thousand times a second; otherwise, virtual surfaces feel softer, or, at worst, instead of feeling a surface, the user feels as if the haptic device is just vibrating in his/her hand.

Several haptic rendering techniques have been developed recently to render virtual objects. Just as in computer graphics, the representation of 3D objects can be either surface-based or volume-based for the purposes of computer haptics. While the surface models are based on parametric or polygonal representations, volumetric models are made of voxels. The existing techniques for haptic rendering with force display can be distinguished based on the way the probing object is modeled: (1) point-based, where the probe is modelled as a point (this model is analogous to exploring and manipulating real objects with only the tip of a stick), (2) ray-based, where the probe is modelled as a line segment (This model is analogous to exploring and manipulating real objects with the entire length of a stick in addition to its tip), or (3) a 3D-object, where the probe is made up of a group of points, line segments and polygon. The type of interaction method used in simulations depends on the needs and complexity of the application. Today, many algorithms exist to render the shape, surface texture, softness, and dynamics of virtual objects.

For descriptions of the issues involved in haptic rendering as well as the algorithms that have been developed, please see [4], [5], [8], [9], and [10].

5. Applications

The addition of haptics to various applications of virtual reality and teleoperation opens exciting possibilities. Three example applications that have been pursued at our Touch Lab are summarized below.

- *Medical Simulators*: Just as flight simulators are used to train pilots, the multimodal virtual environment system we have developed is being used in developing virtual reality based needle procedures and surgical simulators that enable a medical trainee to

see, touch, and manipulate realistic models of biological tissues and organs. The work involves the development of both instrumented hardware and software algorithms for real-time displays. An epidural injection simulator has already been tested by residents and experts in two hospitals. A minimally invasive surgery simulator is also being developed and includes (a) in vivo measurement of the mechanical properties tissues and organs, (b) development of a variety of real-time algorithms for the computation of tool-tissue force interactions and organ deformations, and (c) verification of the training effectiveness of the simulator. This work is reviewed in [9].

- *Collaborative Haptics:* In another project, the use of haptics to improve human-computer interaction as well as human-human interactions mediated by computers is being explored. A multimodal shared virtual environment system has been developed and experiments have been performed with human subjects to study the role of haptic feedback in collaborative tasks and whether haptic communication through force feedback can facilitate a sense of being and collaborating with a remote partner. Two scenarios, one in which the partners are in close proximity and the other in which they are separated by several thousand miles (transatlantic touch with collaborators in University College, London, [11]), have been demonstrated.
- *Brain Machine Interfaces:* In a collaborative project with Prof. Nicoletti of Duke University Medical School, we recently succeeded in controlling a robot in real-time using signals from about 100 neurons in the motor cortex of a monkey [12]. We demonstrated that this could be done not only with a robot within Duke, but also across the internet with a robot in our lab. This work opens a whole new paradigm for studying the sensorimotor functions in the Central Nervous System. In addition, a future application is the possibility of implanted brain-machine interfaces for paralyzed patients to control external devices such as smart prostheses, similar to pacemakers or cochlear implants.

Given below are several more potential applications:

- *Medicine:* manipulating micro and macro robots for minimally invasive surgery; remote diagnosis for telemedicine; aids for the disabled such as haptic interfaces for the blind.
- *Entertainment:* video games and simulators that enable the user to feel and manipulate virtual solids, fluids, tools, and avatars.
- *Education:* giving students the feel of phenomena at nano, macro, or astronomical scales; “what if” scenarios for non-terrestrial physics; experiencing complex data sets.
- *Industry:* integration of haptics into CAD systems such that a designer can freely manipulate the mechanical components of an assembly in an immersive environment.
- *Graphic Arts:* virtual art exhibits, concert rooms, and museums in which the user can login remotely to play the musical instruments, and to touch and feel the haptic attributes of the displays; individual or co-operative virtual sculpturing across the internet.

6. Future Challenges and Opportunities

Many of the issues concerning the development of haptic interfaces and computer haptics are summarized in our previous survey articles. Although both ground-based and exoskeletal force-reflecting haptic interface devices are available in the market, further improvements in range, resolution, and frequency bandwidth of these devices are needed to match their performance with that of the human user. Ability to reflect torques in addition to forces, enough degrees of freedom to permit grasping and two-handed manipulation of objects are high on the list of desirable improvements. In moving towards realistic haptic displays that mimic direct natural touch, tactile displays are probably the most challenging among the technologies that need to be developed. The emerging field of micro-mechanical systems holds promise for providing very fine arrays of tactile stimulators. Although capable of relatively small forces and deflections, arrays of such actuators integrated with addressing electronics are expected to be inexpensive, lightweight, and compact enough to be worn without significantly impeding user's actions.

In the area of computer haptics, the current models of virtual objects that can be displayed haptically in real-time are quite simplistic compared to the static and dynamic behaviour of objects in the real world. Computationally efficient models and interaction techniques that result in real-time haptic displays that match the human perceptual capabilities in accuracy and resolution will continue to be a challenge, even with the current rate of increase in processing speeds. This is because the complexity of the models, such as in detecting collisions of moving multiple objects or in performing a mechanistic analysis of a deformable object in real-time, can be arbitrarily high. Synchronization of the visual, auditory and haptic displays can be problematic, because each modality requires different types of approximations to simulate the same physical phenomenon. Use of multiple processors with shared memory and/or multi-threading seems to be essential. To have haptics across the internet in a manner that is useful to a large number of users, standardized protocols for distributed VEs should include haptics explicitly.

Due to inherent hardware limitations, haptic interfaces can only deliver stimuli that approximate our interactions with the real environment. It does not, however, follow that synthesized haptic experiences created through the haptic interfaces necessarily feel unreal to the user. Consider an analogy with the synthesized visual experiences obtained while watching television or playing a video game. While visual stimuli in the real world are continuous in space and time, these visual interfaces project images at the rate of about 30 frames/sec. Yet, we experience a sense of realism and even a sense of telepresence because we are able to exploit the limitations of the human visual apparatus. The hope that the necessary approximations in generating synthesized haptic experiences will be adequate for a particular task is based on the fact that the human haptic system has limitations that can be similarly exploited. To determine the nature of these approximations, or, in other words, to find out what we can get away with in creating synthetic haptic experiences, quantitative human studies that are tightly coupled with

technology development are essential to assess which types of stimulation provide the most useful and profound haptic cues for the task at hand.

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Note: Most of the articles listed below are our previous review articles, which, in turn, have references to works by us and others for a deeper study of haptics. Many of these documents are available in downloadable pdf format at <http://touchlab.mit.edu>

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