The Potential of Haptics Technologies

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Still only in its infancy, haptics promises to be a revolution in how we interact in the virtual world

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Haptics is a term that was derived from the Greek verb "haptesthai" meaning "of or relating to the sense of touch." It refers to the science of manual sensing and manipulation of surrounding objects and environments through the sense of touch. The "touching" of objects and or environment could be made by humans, machines, or a combination of both; and the objects and environments can be real, virtual, or a combination of both. Also, the interaction may or may not be accompanied by other sensory modalities such as vision or audition. Haptics has brought biomechanics, psychology, neurophysiology, engineering, and computer science together in the study of human touch and force feedback with the external environment.

Touch is a unique human sensory modality in that it enables a bidirectional flow of energy and information between the real, or virtual, environment and the end user. This is referred to as *active touch*. For instance, to sense the shape of an object such as a cup, we have to grasp and manipulate the physical object and run our fingers across its shape and surfaces to build a mental image of the cup. Furthermore, in a manipulation task such as pressing a softball or filling a cup, there is a definite division between input and output, but it is often difficult to define. There is a co-dependence between sensing and manipulation that is at the heart of understanding how humans can so deftly interact with the physical world.

We researchers organize the rapidly increasing multidisciplinary research of haptics into four subareas: human haptics, machine haptics, computer haptics, and multimedia haptics (Figure 1).

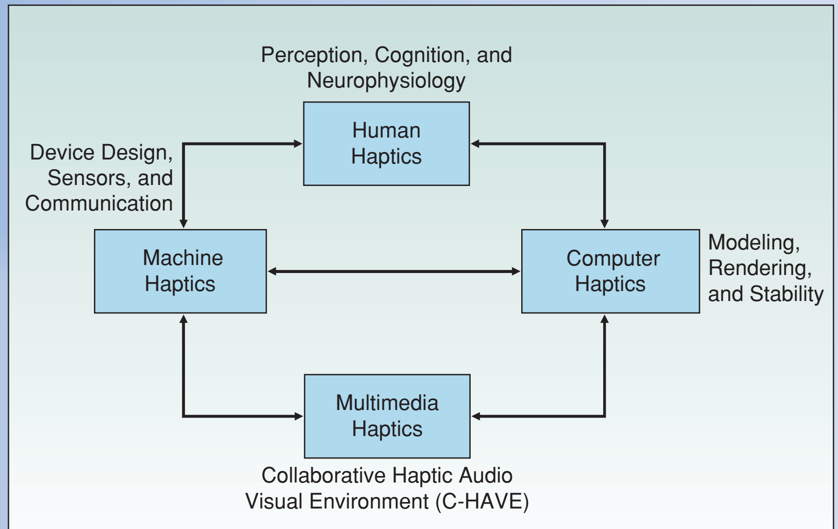

Fig. 1. Interdisciplinary haptic research branches.

Human Haptics

Human haptics refers to the study of human sensing and manipulation through tactile and kinesthetic sensations. When a user touches an object, interaction forces are imposed on the skin. The associated sensory system conveys this information to the brain and thus leads to perception. As a response, the brain issues motor commands to activate the muscles that results in a hand or arm movement. Human haptics focuses mainly on studying this human sensorimotor loop and all aspects related to the human perception of the sense of touch.

The human haptic system comprises four subsystems: the mechanical, the sensory, the motor, and the cognitive. The mechanical component is essentially the arm-hand system. This component consists of the upper arm, the forearm, and the hand, which as a whole, possesses more than 28 degrees of freedom. The sensory or somaesthetic system includes large numbers of various classes of receptors and nerve endings in the skin, joints, tendons, and muscles. Typically, a physical stimulus activates these receptors and causes them to convey sensory information—such as mechanical, thermal, and chemical properties of the touched object—via the afferent neural network to the central nervous system. In the cognitive subsystem, the brain analyzes and perceives the conveyed information and issues appropriate motor commands that activate the muscles resulting in hand or arm movements. The motor subsystem comprises contractile organs (such as muscles) by which movements of the various organs and parts are affected.

Machine Haptics

Machine haptics involve designing, constructing, and developing mechanical devices that replace or augment human touch. These devices are put into physical contact with the human body for the purpose of exchanging (measuring and displaying) information with the human nervous system. In general, haptic interfaces have two basic functions. First, they measure the positions or contact forces of any part of the human body, and second, they compute the information and display the position or forces in appropriate spatial and temporal coordination to the user. Currently, most of the force-feedback haptic interfaces sense the position of their end-effector and display the forces to the user using single point of interaction models.

Computer Haptics

Computer haptics is an emerging area of research that is concerned with developing algorithms and software to generate and render the "touch" of virtual environments and objects, just as computer graphics deal with generating and rendering visual images. Computer haptics has two main components, haptic rendering and visual rendering, that communicate the virtual environment's graphics, sound, and force responses to the human user. Haptic rendering is considered the core of any haptic-based application—it manages algorithms to detect and report when and where the geometry contact has occurred (collision detection) and computes the correct interaction force between a haptic device and its virtual environment (collision response). Visual rendering integrates a number of algorithms and techniques to compute the real-time behavior of the virtual environment's graphics using mathematical expressions or any other modeling techniques.

Multimedia Haptics

Multimedia and information technology are reaching limits in terms of what can be done in multimedia applications with only sight and sound. The next critical step in development in multimedia systems is to bring the sense of "touch" into applications. We define multimedia haptics as *the acquisition of spatial, temporal, and physical knowledge of the environment through the human touch sensory system and the integration/coordination of this knowledge with other sensory displays (such as audio, video, and text) in a multimedia system*. Therefore, multimedia haptics, which we also refer to as a haptic audio visual environment (HAVE), involves integrating and coordinating the presentation of haptic interface data, and other types of media, in the multimedia application to utilize gesture recognition, tactile sensing, and force feedback.

Architecture of Collaborative Haptic Audio Visual Environment (C-HAVE)

Figure 2 shows a C-HAVE block diagram. Haptic rendering comprises a group of algorithms and techniques that compute and generate interaction forces and torques between the haptic interface avatar (the image of a person in virtual reality) and the virtual objects populating the environment. The simulation engine is responsible for computing the virtual environment behavior over time. The visual and auditory modalities have their own rendering algorithms and transducers that convert media signals from the virtual environment into a form the human operator can perceive. The network interface module connects the local haptic system to the collaborative networked environment while facilitating the use of haptics in a network context. This is commonly referred to as telehaptics. It involves transmitting computer-generated touch sensations over networks between physically distant humans.

The Collaborative Virtual Environment (CVE) is a shared virtual world that supports collaborative manipulation of objects in the virtual environment. The CVE consists of a network of computer nodes whose operators could have different kinds of haptic devices to "co-touch" virtual objects, or they could just be passive observers. Many issues are associated with the design of CVE including synchronization, complex control computations, network jitter compensation, and robustness.

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Theory of Operation in Simple Words

How can we make objects that populate the virtual environment touchable? The basic principle of haptic interaction is simple. When a human user manipulates a generic probe (end-effector) of the haptic interface device, the position sensors implanted on the device convey its tip position to the computer. The position of the end-effector correlates with the avatar and updates it accordingly. Every time interval (i.e., 1 ms), the computer that controls the device checks for collisions between the end-effector (simulated stylus) and the virtual objects that populate the virtual environment. If a collision has occurred, the haptic rendering system calculates the reaction forces/torques that should occur at the interaction point and commands the actuators (typically a computer-controlled electric dc motor) that are attached to the device to move, thus leading to tactual perception of the virtual objects. If no collision is detected, no forces will be computed and applied and the user is free to move the haptic device (Figure 3) as if exploring an empty space. Typically, the magnitudes of the reaction forces are assumed proportional to the depth of indentation and the forces are applied along the exterior of the surface being penetrated.

Haptic Interfaces

Haptic interfaces or devices are essentially small robots that exchange mechanical energy with users. From a hardware perspective, a haptic device has one or more input transducers (sensors that measure the positions and/or contact forces

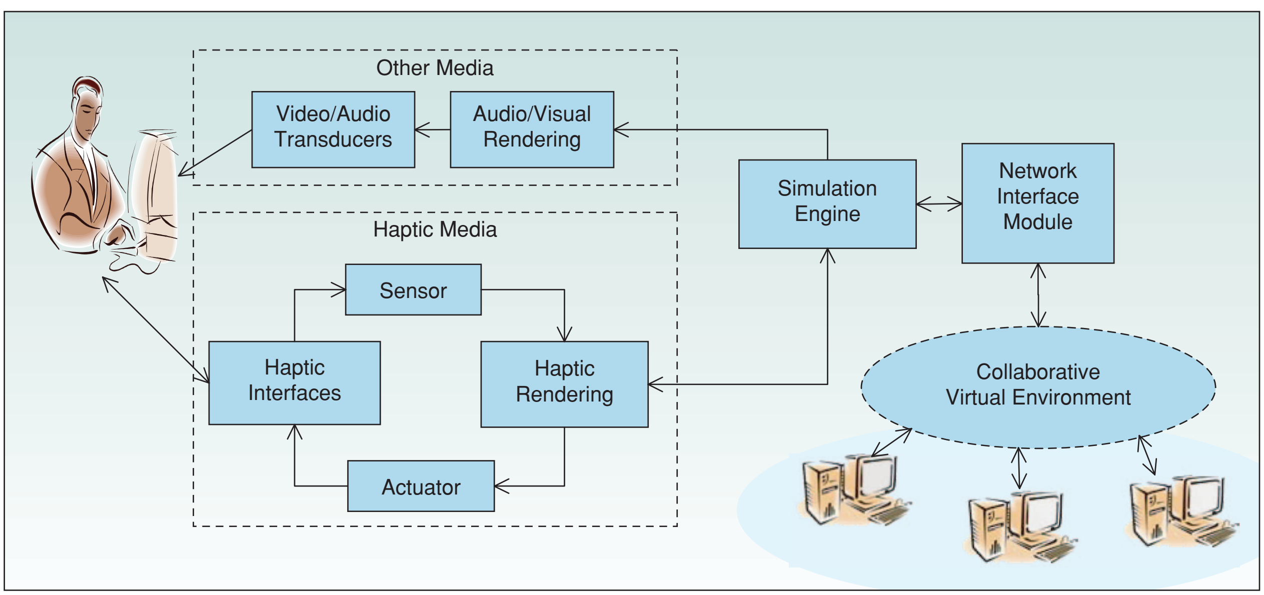

Fig. 2. Virtual reality system with emphasis on haptic modality.

of any part of the human body) and at least one output transducer (actuator that displays contact forces and positions in appropriate spatial and temporal coordination to the user). A cross section of representative haptic interfaces is presented in Figure 3, namely the SensAble Technologies PHANTOM® Omni™, the Immersion CyberForce, and the FCS HapticMASTER.

Two major features characterize haptic devices: the degree of freedom and the haptic refresh rate. The degree of freedom refers to the number of independent axes down or around which the device can exert force or torque. Available devices range from those capable of producing nondirectional forces, such as vibrations, to 6-degree-of-freedom devices that can activate forces along and around all three spatial axes. On the other hand, the haptic refresh rate represents the maximum speed at which the device hardware can generate forces or torques to the user. It has been shown that at least 1 kHz is required (which is a typical value for state-of-the-art devices) to create a smooth illusion of haptic interaction.

Haptic Rendering

Since the term haptic rendering has been widely used in literature and with slightly different meanings, we explicitly define it as the following:

Haptic rendering refers to the group of algorithms and techniques that are used to compute and generate forces and torques in response to interactions between the haptic interface avatar inside the virtual environment and the virtual objects populating the environment.

This definition has many implications:

- First, the avatar is a virtual representation of the haptic interface whose position is controlled by the operator.
- Second, the interaction between avatars and virtual objects is bidirectional; the energy and information flow both from and toward the user. The avatar's geometry and type of contact varies according to the application and can be point-based, multipoint-based, or volumetric objects, consequently regulating the generated forces.
- Third, the ability to find the point(s) of contact is at the core of the haptic rendering process: this is the problem of collision detection, which becomes more difficult and computationally expensive as the complexity of the models increases.
- Fourth, calculating the ideal contact forces is referred to as a force response algorithm: after detecting a collision, the interaction forces between avatars and virtual objects must be computed. These computed forces then generate tactile or kinesthetic sensations.
- Fifth, the generation of the contact forces is an integral part of the haptic rendering package, which creates the "feel" of the object. The haptic device is commanded in such a way that minimizes the error between ideal and applicable forces. The generated force can represent the stiffness of the object, damping, friction, surface texture, etc.
- Finally, all the above-mentioned algorithms must repeat the computations at a rate equal to or higher than 1 kHz, and latency must be low. Inappropriate values of these variables might result in system instabilities.

C-HAVE Applications

Haptic research and development has focused on designing and evaluating several prototypes of different characteristics and capabilities for the use in virtual environments. Recently, some of these prototypes have become commercially available to the market. Applications of this technology have been spreading rapidly from devices applied to graphical user interfaces, games, multimedia publishing, scientific discovery and visualization, arts and creation, editing sound and images, the vehicle industry, engineering, manufacturing, telerobotics, teleoperations, education and training, the military domain, as well as medical simulation and rehabilitation.

Therefore, the applications spectrum is quite vast and its trend of expansion is promising to increase. However, haptic interfaces are not yet ready to become a common device in our homes like a computer. These interfaces have computational

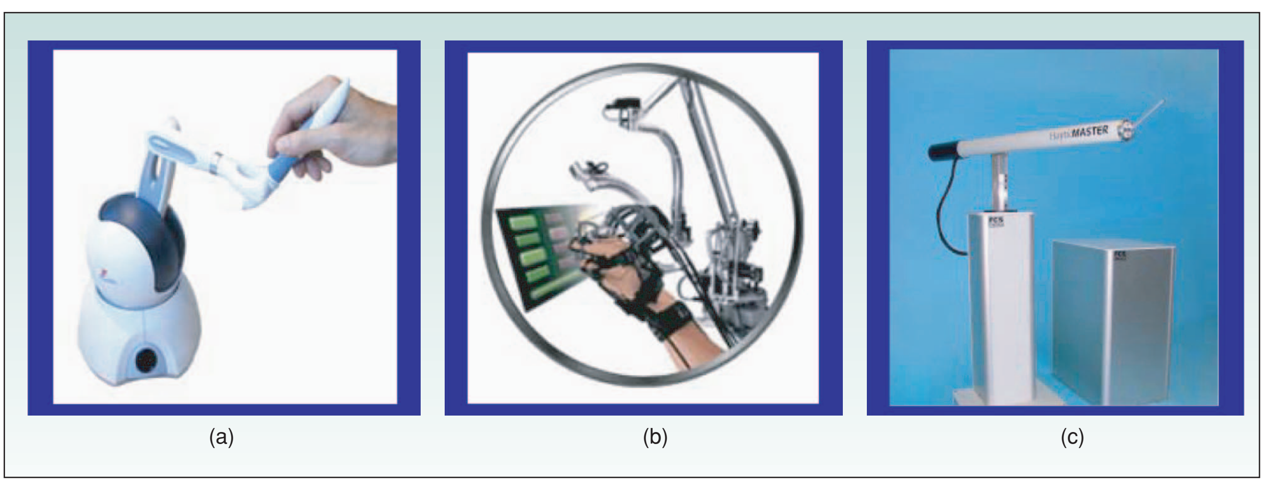

Fig. 3. (a) PHANTOM® Omni, (b) Immersion CyberForce, and (c) FCS HapticMASTER.

challenges that become considerably more demanding as the experience becomes more realistic. The result is generated from the collaboration of coordinating the visual system and tracking the position and updating the forces on the haptic device that delivers or simulates the sensation.

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Data Visualization

Data visualization uses animations or interactive graphics to analyze or solve a problem. Haptic applications for data visualization are classified into two categories: applications for scientific data visualization, and those for visually impaired humans. Incorporating haptics into scientific data visualization allows users to form a high-level view of their data more quickly and accurately. As an example of scientific data visualization, a problem-solving environment for scientific computing called SCIRun has been developed in [1]. The haptic/graphic display is used to display flow and vector fields such as fluid flow models for airplane wings. Another application is the incorporation of haptics into biomolecular simulation. For instance, a system proposed in [2]—called Interactive Molecular Dynamics—allows the manipulation of molecules in a molecular dynamic simulation with real-time force feedback and a graphical display. Finally, at the University of North Carolina, haptic devices have been used for haptic rendering of high-dimensional scientific datasets, including three-dimensional (3-D) force fields and tetrahedralized human head volume datasets.

To date, there has been a modest amount of work performed on the use of machine haptics for the visually impaired. For instance, haptics have been applied to mobility training [3] where the system utilizes the touch information channel to provide blind persons with information about a site that will be visited (such as business name, types and locations of doors, and types of traffic control devices). A real city block and its buildings can be explored with the PHANToM haptic device, using graphical models of the buildings populating the city.

Medical Simulation and Rehabilitation

The medical area has been an abundant source of haptic development. Introducing haptic exploration as the medium of training has revolutionized many surgical procedures over the last decade. Surgeons used to rely more on the feeling of net forces resulting from tool-tissue interactions and needed surgical experience to operate successfully on patients. Haptic applications include surgical simulations, telesurgery systems, rehabilitation, and medical training.

Haptic-based surgical simulators address many of the issues in surgical training. First, they can generate scenarios of graduated complexity. Second, new and complex procedures can be practiced on a simulator before proceeding to a human or animal. Finally, students can practice on their own schedule and repeat the practice sessions as many times as they want. Surgical simulators have been surveyed in [4] and can be classified according to their simulation complexity as needle-based, minimally invasive surgery, and open surgery.

Telesurgery systems involve two additional issues: coherency of the virtual scenes among all participating users and force feedback stability when haptic information is sent over nondedicated and nonreliable channels, such as the Internet. A telesurgery system comprises three components: a master console (surgeon side), a communication channel for bilateral control, and a slave robot (patient side). At the University of Ottawa, Georganas, et al., developed a hapto-visual eye cataract surgery training application [5]. The application supports three scenarios: an instructor and a trainee—in distinct physical locations—interacting in real-time in a telementor fashion, a trainee learning the surgical procedure by means of perceptual cues, and a trainee performing the surgery without any guidance.

Haptic applications in rehabilitation involve applying certain forces to the injured or disabled organ (such as the finger, arm, or ankle) to regain its strength and range of motion. Haptic interfaces show clear benefits in imitating a therapist's exercises with the possibilities of position and force control. A lot of research has been performed in the area of haptic applications for rehabilitation and medical training [6].

E-Commerce

As for electronic commerce, or e-commerce, force feedback would allow the consumer to physically interact with a product. Human hands are able to test a product by feeling the warm/cold, soft/hard, smooth/rough, and light/heavy properties of surfaces and textures that compose a product. Consumers usually like to touch certain products (such as bed linens and clothes) in order to try them before they buy.

Surprisingly, little work has been completed in the field of haptic-enabled e-commerce. For example, Shen, et al., proposes a scenario for the online experience of buying a car [7]. A virtual car showroom is created along with avatars for both the customer and the salesperson to communicate in real-time. The customer avatar can perform haptic-based functions inside the car such as turn on/off the ignition and the sound system.

Education

There is a growing interest in the development of haptic interfaces to allow people to access and learn information in virtual-reality environments. A virtual-reality application combined with haptic feedback for geometry education has been recently investigated [8]. The proposed system allows a haptic 3-D representation of a geometry problem, its construction, and the solution. The performance evaluation showed that the system is user friendly and provides a more efficient learning approach.

A system for constructing a haptic model of a mathematical function using the PHANToM haptic device has been introduced and implemented in [9]. The program accepts a mathematical function with one or two variables as input and constructs a haptic model made of balsa wood with the trace of the function carved into its surface.

Current haptic technology suffers from a number of limitations ranging from the high price and weight or size of the haptic interface to limitations in workspace and the lack of force feedback to the body.

Another application that simulates a catapult has been developed to enable users to interact with the laws of physics by utilizing a force feedback slider (FFS) interface [10]. The FFS is a motorized potentiometer limited to one degree of movement (push/pull along a line) through which the user grabs the slider and moves the handle. It has been shown that force feedback helps users in creating a mental model to understand the laws of physics.

Entertainment

Haptic research in the realm of home entertainment and computer games has blossomed during the past few years. In general, the game experience has four pillar aspects: physical, mental, social, and emotional. In particular, force feedback technology enhances the physical aspects of the game experience by creating a deeper physical feeling of playing a game, improving the physical skills of the players, and imitating the use of physical artifacts.

Many researchers have introduced complex haptic-based games. For instance, haptic battle pong is an extension of pong with haptic controls using the phantom device [11]. A haptic device is used to position and orient the paddle while force feedback is used to render the contact between the ball and the paddle. The Haptic Airkanoid is another ball-and-paddle game where a player hits a ball against a brick wall and feels the rebound of the impact [12]. It has been shown that playing the haptic version is more fun even though the vibration feedback is not realistic.

Arts and Designs

Haptic communication opens new opportunities for virtual sculpting and modeling, painting, and museums. Sculpting and modeling arts are innately tactile; therefore the introduction of touch in virtual sculpting is explicitly important to the language inherent in sculptural forms. As for painting, haptics has a clear merit in recreating the "sight, touch, action, and feel" of the artistic process [13]. Furthermore, haptic modality is a significant asset for virtual art exhibitions as it allows an appreciation of 3-D art pieces without jeopardizing the conservation standards.

Audio Applications

Adding audio makes haptic-based systems closer to the real simulation. Users can interact with more sensory channels and be immersed in simulations that are more realistic. Modeling the sound produced when objects collide is the objective of a haptic interface that intends to provide more realism in feeling a fabric's roughness, friction, and softness. A method to build an audio-haptic interface by using a rigid stylus is presented in [14]. A user can touch the virtual fabric via a virtual rigid stylus, perceive the surface roughness, friction and softness, and hear the stylus' rubbing sound.

Current Challenges and Emerging Trends

Current haptic technology suffers from a number of limitations ranging from the high price and weight or size of the haptic interface to limitations in workspace and the lack of force feedback to the body. Also, not to be ignored are the high bandwidths, the low network latency, the high stability, and the synchronization requirements of haptics that are not met by the current state-of-the-art. In the following, we pinpoint some challenges and trends in current haptic technology and research:

Large Haptic Interface Weight/Size

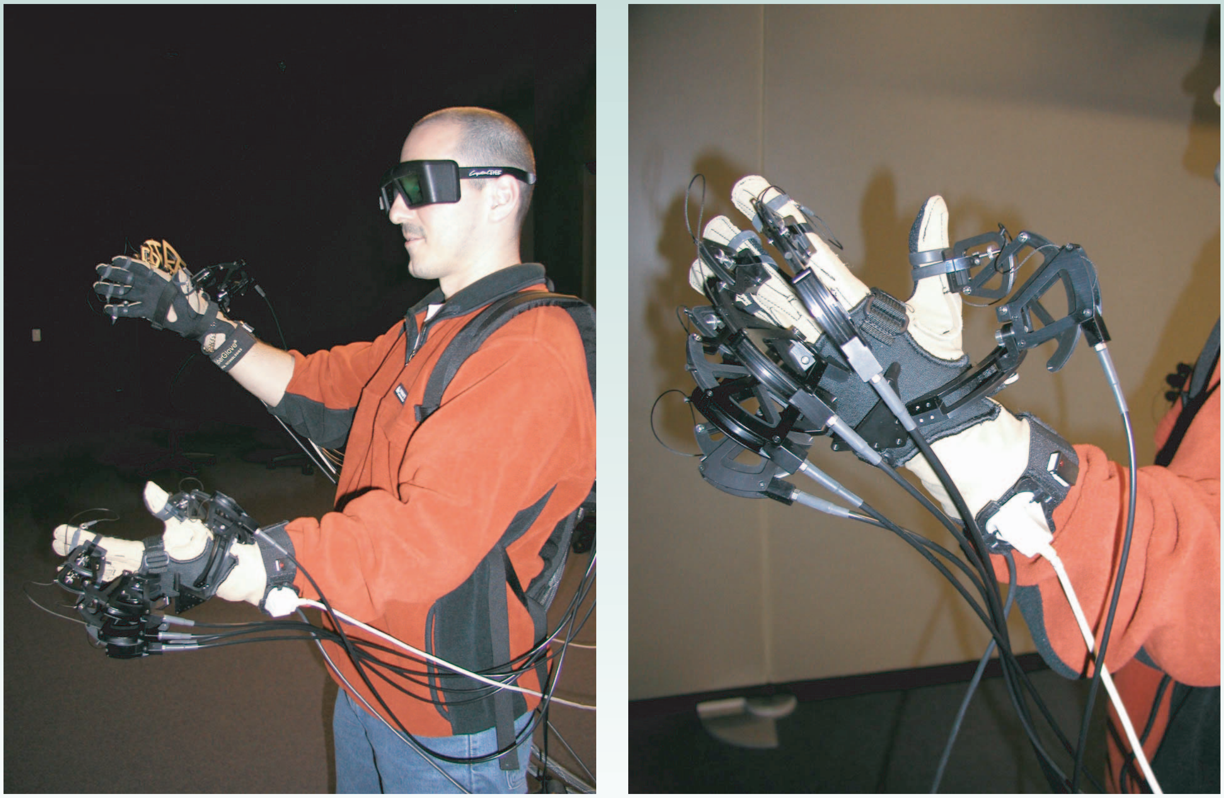
One of the major shortcomings of haptic interfaces—particularly wearable ones—is their large weight and/or size. For instance, the CyberGrasp (Figure 4) with an approximate weight of 400 grams is considered tiring for a user during lengthy simulations.

Bandwidth Limitations

One of the biggest challenges in C-HAVE data transmission over the Internet is the limited available bandwidth. The fact that haptic data is too bulky, relative to the available bandwidth, implies that there will be improper registration between what the users see on the screen and what they feel. The situation should improve when better haptic based compression techniques are introduced.

Latency

In networked haptic applications, latency is universally detrimental, as it may cause not only a time lag between a human operator and the force feedback but also system instability such as vibrations of reaction forces. Latency is introduced in either of these two forms: haptic rendering latency and network latency.



(a) (b)

Fig. 4. (a) The CyberGrasp haptic device in action. (b) A close up of the CyberGrasp.

Interoperability of Haptic Interfaces

Many haptic devices are very procedure- and application-specific and are developed for a specific purpose. Consequently, the adaptation to innovative tasks requires significant analysis and implementation of new systems to overcome particular device limitations. Therefore, a uniform controlling mechanism that makes full use of the device capabilities in accordance with each user's personal needs is considered as one of the critical issues in haptic technologies.

Instability and Vibration

While update rates of 60 Hz are fast enough for graphics rendering, haptic update rates need to be approximately 1,000 Hz. If update rates fall below that value, the haptic device becomes unstable and vibrates when we touch virtually hard surfaces.

Haptics for Biometrics

Biometric systems identify users based on their behavioral or physiological characteristics. The potential of haptic technology is significant to continuously authenticate and control access to high security applications/systems for many reasons. First, conventional security systems, such as password-based or a physical biometric, can only assure the presence of the correct person at the beginning of the session; it cannot detect if a hacker takes over the control. Second, traditional authentication means, such as a login ID and passwords, can be easily compromised whereas haptic-based biometric systems are significantly more difficult to compromise [15]. In a typical scenario, a haptic system measures the position, velocity, force, and torque data as users perform a specific task. Afterward, feature-extracting algorithms and techniques could be used to extract biometric features and build physical patterns that uniquely/universally identify the user. Though it may be difficult to develop a highly accurate identification and recognition haptic-based system using the current state-of-the-art haptic technologies, it is an avenue worth pursuing.

Haptic Playback

Traditional training methods, such as books and lectures, are not effective in teaching interaction tasks. Haptic interfaces can be used to provide physical interactions with trainees; thus decreasing the trainees-to-trainer ratios. The task of playing prerecorded haptic stimuli to a user to convey the information on followed position and exerted forces is called haptic playback. As an example, haptic playback could also be useful in medical training where the motions of an expert may be recorded and saved for later "playback" by a trainee. A haptic device is programmed to provide the same predefined trajectory and controlled forces for training the user's motor-control skills. For the time being, haptics playback remains an example of uncharted territory in haptics research.

Haptic on a Chip

Only recently, the use of wireless tactile sensing devices has emerged and has shown a potential research avenue. An important design goal of wireless haptic devices is to increase the workspace region and to eliminate extraneous forces caused by tension in the connecting cables. A tentative research list could include the following: improvements in the sampling rates and available bandwidth, increase in the degree of freedom of force exerted at the device-body interface, and integration with well-established wireless technologies such as Bluetooth.

Haptic Data Compression

The demands for real-time simultaneous recording and transmission of voluminous data produced by multiple sensors are thrusting toward the exploration of haptic data compression [16]. However, despite the stringent need for haptic data compression, the field is still in its infancy and many open areas have emerged. There is a need to investigate the following aspects:

- the development of a system for the real-time compression of heterogeneous haptic information
- exploration of the suitability of existing compression techniques for haptic data
- the introduction of methods to evaluate the perceptual impact of compression of haptic data. Another possibility is to extract semantic information from the sampled haptic data that would help in reducing the amount of data required to describe a session and thus enabling efficient storage/transmission of haptic data.

Conclusions

In spite of the significant recent progress, the incorporation of haptics into virtual environments is still in its infancy due to limitations in the hardware, the cost of development, as well as the level of reality they provide. Nonetheless, we believe that the field will one day be one of the groundbreaking media of the future. It has its current holdups but the promise of the future is worth the wait. The technology is becoming cheaper and applications are becoming more forthcoming and apparent. If we can survive this infancy, it will promise to be an amazing revolution in the way we interact with computers and the virtual world.

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