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A guided tour in haptic audio visual environments and applications

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Abstract: The science of haptics has received enormous attention in the last decade. Activities in different disciplines such as robotics, computer graphics, and psychophysics have been the foundation of haptic science. Nowadays, haptic research comprises four interdisciplinary research branches: human haptics, machine haptics, computer haptics, and the newly introduced multimedia haptics. This paper traces the evolution of haptics technology from the introductory concepts and haptic system architecture, to current technology in the four haptics research branches and applications. Finally, we summarise our findings and present a vision for overcoming challenges and our direction for future research in this area.

Keywords: haptics; haptic applications; haptic challenges; haptic rendering; haptic perception; haptic interfaces.

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1 Introduction

Haptics, a term that was derived from the Greek verb ‘haptesthai’ meaning ‘to touch’, refers to the science of sensing and manipulation through touch. This word was introduced at the beginning of the 20th century by researchers in the field of experimental psychology to refer to the active touch of real objects by humans. In the late 1980s, the term was redefined to enlarge its scope to include all aspects of machine touch and human-machine touch interaction. The ‘touching’ of objects could be made by humans, machines, or a combination of both; and the environment can be real, virtual, or a combination of both. Currently, the term has brought together many disciplines including biomechanics, psychology, neurophysiology, engineering, and computer science to refer to the study of human touch and force feedback with the external environment.

1.1 Haptics history: from psychophysics to multimedia

Haptics was introduced at the beginning of the 20th century through research performed in the field of experimental psychology, aimed at understanding human touch perception and manipulation. Psychophysical experiments provided the contextual clues involved in the haptic perception between the human and the machine. The areas of psychology and physiology provided a fresh look into the study of haptics and it remained popular until the late 1980s. Researchers have found that the mechanism by which we feel and perceive the tactual qualities of our environment is considerably more complex in structure than, for example, our visual modality. However, they opened up a wealth of opportunities in academic research to answer the question of machine haptics.

Turning to the robotics arena – in the 1970s and 1980s – most researchers were considering the system’s aspects of controlling remote robotic vehicles to manipulate and perceive their environments by touch. The main objective was to create devices with dexterity and inspired by human abilities. Robotic mechanical systems, with a human being in their control loop, are referred to as Tele-manipulators (Petriu et al., 1982). An intelligent machine is expected to perceive the environment, reason about the perceived information, make decisions based on this perception, and act according to a plan specified at a very high level (Angeles, 2002). In time, the robotics community found interest in topics including, but not limited to: sensory design and processing, grasp control and manipulation, object modelling and haptic information encoding.

Meanwhile, terms such as Tele-operation, Tele-presence, and Tele-robotics were managed interchangeably from the robotic community until the mid-90s. From those terms, two were especially important to develop haptic systems, Tele-operation and Tele-presence. Tele-operation refers to the extension of a person’s sensing and manipulation capabilities to a remote location. Tele-presence can be described as a realistic way that an operator can feel physically present at a remote site. Motivated by these concepts; the Tele-presence and Tele-operation research community developed several projects in fields such as the nuclear industry, the sub-sea industry, and in the space and military markets.

In the early 1990s, the use of the word haptics in the context of computer haptics was introduced. Much like computer graphics, computer haptics is concerned with the techniques and processes of generating and displaying haptic stimuli to the user (Srinivasan and Basdogan, 1997). In fact, computer haptics uses digital display technology as the medium of physically tangible interaction where objects can be simulated in an interactive manner. This new modality presents information to the user's hand, or other parts of the body, by exerting controlled forces through the haptic interface. These forces are delivered to the user depending on the physical properties of the objects that can be perceived. The hardware components of this interface play an important role in displaying these forces through the response sensors to the user. Unlike computer graphics, the behaviour of haptic interaction is bidirectional, due to the energy and information flow in both directions from the user to the interface and vice versa.

Only recently have haptic technologies been integrated with high-end workstations for Computer-Aided Design (CAD) and – at the lower end – on home PCs and consoles, to augment the human-computer interaction. Effectively this implies opening a new mechanical channel between human and computer so that data can be accessed and manipulated through haptic interfaces. Nowadays, computer haptic systems can display objects of sophisticated complexity and behaviour. This is possible due to the availability of high-performance force-controllable haptic interfaces, affordable computational geometric modelling and collision detection and response techniques, which provide a good understanding of the human perceptual needs, and a dramatic increase in the processing speed and memory size. With the commercial availability of haptic interfaces, software toolkits, and haptics-enabled applications, the field is experiencing an exciting exponential growth.

Kinesthetic and haptic sensations allow for multimedia applications, which utilise gesture recognition and force feedback. In addition to traditional media such as image, audio, and video, haptic – as a new media – plays a prominent role in making real-world objects physically palpable in a Collaborative Virtual Environment (CVE). For instance, Collaborative Haptic Audio Visual Environments (C-HAVE) allow multiple users, each with his/her haptic interface, to collaboratively and/or remotely manipulate shared objects in a virtual environment. The potential of haptics as a new media is quite significant for many applications such as Tele-presence, Tele-learning, Tele-medicine, Tele-operation in hazardous environments, industrial design and testing, gaming, and any related interactive virtual reality application.

1.2 Interdisciplinary haptic researches

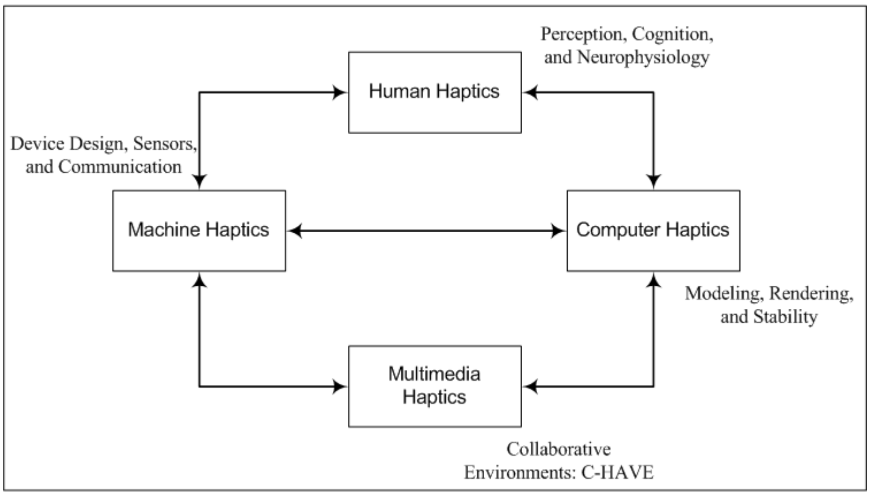
In this paper, we organise the rapidly increasing multidisciplinary research literature into four sub-areas:

- human haptics
- machine haptics
- computer haptics
- multimedia haptics (see Figure 1).

Human haptics refer to the study of human sensing and manipulation through tactile and kinesthetic sensations. It comprises human haptic perception, cognition, and neurophysiology brought together to contribute to the study of human touch and physical interaction with the external environment. Machine haptics involve designing, constructing, and developing mechanical devices that replace or augment human touch.

These interfaces are put into physical contact with the human nervous system for the purpose of measuring and displaying touch information.

Figure 1 Interdisciplinary haptic research branches

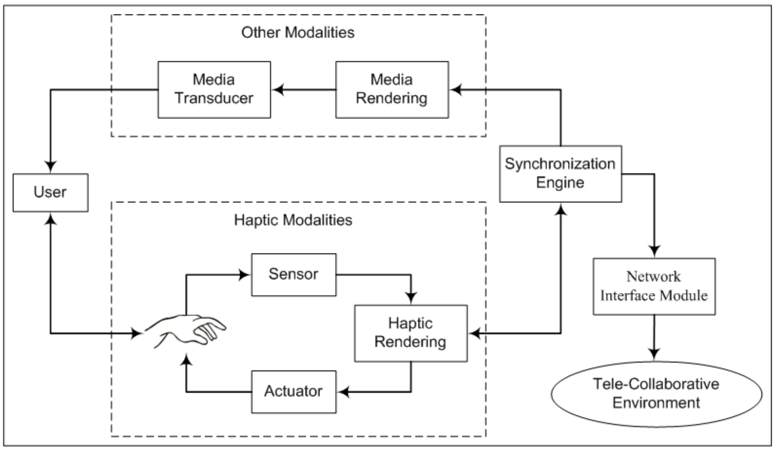


Computer haptics is an emerging area of research that is concerned with developing algorithms and software to generate and render the 'touch' of virtual environment objects – somehow analogous to computer graphics. Essentially, computer haptics deals with modelling and rendering virtual objects for real-time display. It includes the software architecture for haptic interactions and the synchronisation with other display modalities such as audio or visual media. Multimedia haptics involves integrating and coordinating the presentation of haptic interface data and other types of media in multimedia applications to utilise gesture recognition and force feedback.

1.3 Components of a haptic system

The haptic system block diagram is shown in Figure 2. Haptic rendering samples the position sensors at the haptic interface device joints to obtain the avatar's position inside the virtual environment. The position information is used to check for collisions between objects and avatars, and to compute force responses that are in turn applied on the operator through the actuators. The simulation engine is responsible for computing the virtual environment's behaviour over time. The visual and auditory rendering algorithms compute the virtual environment's graphics and sound. The audio/video transducers convert audio and visual signals from the computer into a form perceivable by the human operator. Notice that the audio and visual channels feature unidirectional information and energy flow (from the simulation engine to the end user), whereas the haptics modality exchanges information and energy in two directions (from and toward the user).

Figure 2 Components of a haptic system



The network interface module connects the local haptic system to the collaborative networked environment while facilitating the use of haptics in a network context, which is commonly referred to as Tele-haptics. This involves transmitting computer generated touch sensations over networks between physically distant devices and/or humans. 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 can just be passive observers. Many issues are associated with the design of CVE including synchronisation, complex control computations, network jitter compensation, and robustness.

The remainder of this paper is structured as follows. In Section 2, we provide an overview of the four major interdisciplinary haptic researches and a more in-depth look at the definition and the current research efforts for each. Several exciting applications of haptics in various domains are described in Section 3. The applications classification is performed in accordance with the application domains that are benefiting from haptic interactions such as medicine, education, entertainment, arts, and e-commerce. Section 4 presents a discussion of challenges and limitations that are facing the haptics research community, such as the interface size and weight, and the limited bandwidth. In Section 5, we provide a discussion of future opportunities and recommend directions for further research in haptics. Finally, we conclude by summarising the paper contents and briefly formulate our findings.

2 Interdisciplinary haptic researches

2.1 Human haptics

In order to optimise the interaction with the human user, it is vital to understand how the mechanical, motor, cognitive, and sensory subsystems of the human haptic system work. The mechanical structure serves to define the number of Degrees of Freedom (DOF) of motion. For instance, the human hand has 19 bones, about 19 joints, and 40 muscles, to provide 22-DOF. The motor subsystem comprises contractile organs (such as muscles) by which movements of the various organs and parts are affected. The cognitive system utilises psychologically plausible computation representations of human haptic processes to augment the perceptual capabilities of human users. The sensory subsystem includes a large number of receptors and nerve endings that sense stimuli and transmit electrical impulses to the central nervous system.

The haptic sensory is distinguished as tactile, kinaesthetic (sometimes called proprioceptive), or a combination of both stimulations. Tactile information is conveyed when the human hand is passive and stationary when placed in contact with an object, whereas kinesthetic information is expressed during active and free motion of the hand. At any rate, all sensing and manipulation interactions that are performed actively with the normal hand involve both types of information. In the following subsections, we describe these two types of information and how they are conveyed.

2.1.1 Tactile mechanoreceptors

Tactile stimulation refers to the sense of the natural physical contact with the ambient environment. Tactile sensations that the hand can experience are quite wide. These include pressure, texture, puncture, thermal properties, softness, wetness, and friction-induced phenomena such as slipping, adhesion, and micro failures as well as local features of objects such as shape, edges, embossing and recessed features. Biologically speaking, there are four kinds of sensory organs (receptors) in the hairless skin of human beings that mediate the sense of touch. These are the Meissner's Corpuscles, Pacinian Corpuscles, Markel's Disks, and Ruffini Endings (Burdea and Coiffet, 2003). Their sensitivity depends on their size, density, frequency range, and nerve fibre branching. On the other hand, hairy skin receptors are characterised by a low special resolution, indicating that they do not effectively perceive a specific geometric structure of a surface or object. Consequently, actuators in a haptic device for texture perception must be applied at hairless skin areas (such as on the palms and fingertips), while those conveying vibratory information could be activated anywhere on the body (Hale and Stanney, 2004).

Scientists have investigated several tactile perception features, including the rate of adaptation of the receptors to a stimulus, the location of the receptors within the skin, the mean receptive areas, the spatial resolution, the response frequency rate, and the frequency for maximum sensitivity. As input parameters, the mentioned hand's features provide guidance in the design and evaluation of the haptic interfaces.

In summary, tactile sensing is an important interface in the role of contextually discriminating and manipulating an object. In the processes of haptic exploration, the lack of tactile feedback makes certain tasks more difficult. Adding different sensing environments through innovative sensors and modelling approaches to represent a physical interaction supports the haptic perception and exploration of the current devices. Currently, there are varieties of commercial and developmental products that provide a diverse range of tactile sensations, some of which are presented in Table 1.

Table 1 Commercial and development tactile-haptic interfaces

	Product	*Description*	*Sensation*	*Vendor*
Commercial Interfaces	CyberTouch	Vibro-tactile stimulators: six (one on each finger, one on the palm)	Pulses or sustained vibration	Immersion Corporation
	Touch Master	Four Vibrotactile stimulators (each finger)	Vibration	EXOS, Inc. (Microsoft)
	CyberGrasp	Force-reflecting exoskeleton: five actuators, one for each finger	Resistive force feedback	Immersion Corporation
	Tactool System	Two fingers	Impulsive vibration	Xtensory, Inc.
	Displaced Temperature System	Via thimble	Temperature change	CM Research, Inc.
Research and Development	HAPTAC	Tactile feedback	Electric pulses Shape Memory Alloy (SMA)	Armstrong Laboratory
	Prototype Tactile Shape Display	Two-fingered hand with two DOFs in each finger.	Electric pulses (SMA)	Harvard University USA
	Temperature Display	Fingertip bed	Temperature feedback	Hokkaido University Japan
	Electrorheological fluids for tactile displays	Colloidal dispersion of malleable oil and dielectric solid particulate	Oil malleability	Hull University, UK
	Tactile display with flexible endoscopic forceps	Distal shaft of the forceps	Contact pressure sensations	Research Centre at Karlsruhe, Germany
	Tactile Display	Thumb, index finger, middle finger, and palm simultaneously	Tactile stimulus	Sandia National Laboratories

2.1.2 Kineasthetic receptors

Kinaesthesia provides humans with an awareness of the position and movement of limbs along with the associated forces that are conveyed by the sensory receptors and the neural signals that are derived from motor commands. The movement can be either self generated or externally imposed by means of sensory organs (receptors) that are found in the skin, the joints, and/or the muscles.

The receptors that support kinaesthetic senses are classified into four categories: Golgi and Ruffini endings (contained in the joints), and Golgi tendons and muscle spindles (contained in the muscles).

These receptors, combined, provide information about joint angles, muscle length and tension, and their rates of change. This information, such as the moving of joints, the movement's velocity, the contractile state of the muscles controlling the joint, along with the information from motor and cognitive systems, produce the perceived limb position and movement. It is worth mentioning that the force control and perceptual bandwidths of the human differ. For instance, it has been proven that the maximum frequency with which a typical hand can command motion is 5–10 Hz, while the position and force signals bandwidth ranges from 20 to 30 Hz (Brooks, 1990).

Researchers are collaborating to develop a detailed catalog of human factors data that aids in better design and evaluation of haptic devices. Tan et al. (1994) showed that the force required for a human to perceive surface hardness ranges from 153 to 415 N/cm. The maximum controllable force ranges from 16.5 to 192.3 N depending on the joint at which the force is applied and the gender of the human. Force output resolution is about 0.36 N and it tends to decrease from the PIP finger joint to the shoulder joint. The Just-Noticeable Difference (JND) for pressure perception is roughly 0.06–0.09 N/cm and it is proven to have a negative slope of 0.25 as a function of the pressure contact area.

2.2 Machine haptics

Machine haptics refers to the design, construction, and use of mechanical devices that are put into physical contact with the human body for the purpose of exchanging information with the human nervous system. In general, haptic interfaces have two basic functions. Firstly, they measure the positions and/or contact forces of any part of the human body, and secondly they display contact forces and positions 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.

Due to the fact that haptic interface devices perform by exchanging mechanical energy with users, they can be catalogued as small robots (Salisbury et al., p.4). One way to distinguish between haptic interface devices is by their grounding locations (examples are ground-based and body-based). Another possible classification is according to the number of DOF of motion or force present at the device/body interface. The desirable characteristics of haptic interface devices include, but are not limited to, the following:

- symmetric inertia, friction, stiffness, and resonate-frequency properties
- balanced range, resolution, and bandwidth of possible sensing and force reflection
- low back-drive inertia and friction (Salisbury et al., 2004).

2.2.1 Tactile interfaces

Several kinds of receptors have been found to mediate tactile sensation in the skin or in the subcutaneous tissues. Many proposed mechanisms use mechanical needles that are activated by electromagnetic technologies (such as solenoids and voice coils), piezoelectric crystals, Shape Memory Alloys (SMA), pneumatic systems, and heat pump systems. Other technologies are based on electrorheological fluids that change the viscosity, thus changing the rigidity upon the application of the electric field. Medical-specific technologies such as electro-tactile and neuromuscular stimulators are still under development.

A survey of tactile interface devices that have been developed so far can be found in Benali et al. (2004) yet they are beyond the scope of this paper. Currently, few tactile interface devices are commercially available (examples are Touchmaster by EXOS Inc., Tactool system by Xtensory, and Teletact Glove by Intelligent Systems Solutions). On the other hand, the majority of research groups focus on the development of tactile interfaces as tools to support the following: investigation into the human tactile sense, hand rehabilitation, and Tele-operation. Examples of research and development of tactile displays are HAPTAC from the Armstrong laboratory, linear and planar graspers developed by the Touch lab at MIT, a temperature display at Hokkaido University, a prototype tactile shape display at Harvard University, a programmable tactile array by the TiNi Alloy Company, and a tactile feedback glove at the University of Salford.

Petriu and his colleagues introduced a tactile sensor with a high sampling resolution (1.58 mm pitch) for active perception of stationary polygonal objects (Petriu and McMath, 1992; Yeung et al., 1994). The experimental tactile sensor consists of a 16-by-16 matrix of force-sensing resistor elements, and has an elastic overlay with protruding tabs, which provides the spatial sampling. Furthermore, a model-based method for blind tactile recognition of 3D objects is proposed in Petriu et al. (2004). The geometric symbols representing terms of a Pseudorandom Array (PRA) are embossed on object surfaces. The method was tested on two 3D polygonal objects: a cube and a parallelepiped. In 2005, they developed an intelligent multimodal sensor system to enhance the haptic control of robotic manipulations of small 3D objects (Payeur et al., 2005). The sensor system is mounted on the end-effector of a manipulator arm – with a relatively high resolution of 1/16 – to refine laser range 3D maps of fine interaction scenarios.

In summary, tactile sensing is an important interface in the role of contextually discriminating and manipulating an object. In the processes of haptic exploration, the lack of tactile feedback makes certain tasks more difficult. Adding different sensing environments through innovative sensors and modelling approaches to represent physical interaction supports the haptic perception and exploration of the current devices. Currently, there are a variety of commercial and development products that provide a diverse range of sensations (see Table 1).

2.2.2 Kineasthetic interfaces

Essentially, kinaesthetic interfaces – or force feedback interfaces – have three main functions:

- measuring the movements and forces exerted by a part of the human body (examples: hand or fingers)
- calculating the effects of these forces on objects in the virtual environment and the force response that must act on the user
- applying the appropriate forces to the user.

Technologies that are currently in use are electromagnetic motors, hydraulics, pneumatics, and SMA.

Other technologies such as piezoelectric motors and magnetoresistive materials have been investigated yet are still the subject of further research and development.

There are a large number of existing kinesthetic interfaces – with quite different types and capabilities – that are now commercially marketed or developed by research groups; a comprehensive survey can be found in Biggs and Srinivasan (2002). The majority of these devices can be classified as exoskeleton devices, tool-based devices, thimble-based devices, or robotic graphics systems. Exoskeleton devices, such as the Force Exoskeleton ArmMaster, deliver forces to the shoulder, elbow, wrist, and finger joints. Tool-based devices deliver forces to the human hand via a knob, joystick, or a pen-like object carried by a user (examples are HapticMaster and Impulse Engine 3000 devices). The most commonly used thimble-based device is the PHANToM, which delivers force to the user's fingertips. Finally, robotic graphics systems use real objects to provide forces to the user's hand. A summary of commercial and research kinesthetic devices is provided in Table 2.

Table 2 Commercial and development kinesthetic-haptic interfaces

	Product	*Description*	*Sensation*	*Application*	*Vendor*
Commercial interfaces	Force Feedback Master	Desktop	Hand via joystick	3D Interaction	EXOS, Inc. (Microsoft)
	Force Exoskeleton ArmMaster	Exoskeleton	Shoulder and elbow	3D Interaction	EXOS, Inc. (Microsoft)
	Impulse Engine 3000	Desktop	Hand via joystick	Surgical procedure	Immersion Corporation
	Laparoscopic Impulse Engine	Desktop	Hand via tool handle	Surgical procedure	Immersion Corporation
	Interactor	Vest	Torso via vest	Entertainment	Aura Systems, Inc.
	Interactor Cushion	Cushion	Back via cushion	Entertainment	Aura Systems, Inc.
	HapticMaster	Desktop	Hand via knob	3D Interaction	Nissho Electronics Corporation
	Hand Exoskeleton Haptic Display	Exoskeleton	Thumb and index finger joints, palm	Virtual pick-and-place tasks	EXOS, Inc. (Microsoft)
	PER-Force 3DOF	Desktop	Hand via joystick	VR and Tele-operation	Cybernet Systems Corporation
	PER-Force Handcontroller	Desktop	Hand via joystick	Space Station	Cybernet Systems Corporation
	PHANToM	Desktop	Fingertip via thimble	VR and Tele-operation	SensAble Devices, Inc.
	SAFiRE	Exoskeleton	Wrist, thumb and index finger	Dynamic simulation	EXOS, Inc. (Microsoft)

Table 2 Commercial and development kinesthetic-haptic interfaces (continued)

	Product	*Description*	*Sensation*	*Application*	*Vendor*
Research and development	Robotic Graphics Proof-of-Concept System	Robotic graphics	Hand via tracker	Aerospace vehicles	Boeing Computer Services
	Force and Tactile Feedback System (FTFS)	Robotic graphics	Throttle and joystick)	Design verification and flight training	Computer Graphics Systems Development Corporation
	Elbow Force Feedback Display	Exoskeleton	Elbow joint	VE simulation	Hokkaido University
	MSR-1 Mechanical Master/Slave	Tool-based	Active limbs	Training	MIT
	Seven DOF Stylus	Tool-based	Hand via tool handle	Tele-operation	McGill University
	Force Feedback Manipulator	Desktop	Hand via joystick	VE simulation	Northwestern University
	Second Generation Rutgers Master	Thimble-based	Three fingertips and thumb	Virtual Knee Palpation System	Rutgers University
	SPICE	Robotic graphics	Hand via tool handle	User interfaces for CAD 3D modelling	Suzuki Motor Corporation
	SPIDAR	Thimble-based	Thumb and index finger	3D Interaction	Tokyo Institute of Technology
	Molecular Docking Virtual Interface	Exoskeleton	Shoulder and elbow	Nanomanipulation molecular docking	University of North Carolina
	Pen-Based Force Display	Tool-based	Fingertips or pointed object	Medical microsurgery	University of Washington

To evaluate the quality of force feedback systems (Rosenberg, 1996) has proposed a set of minimum performance standards. The author recommends a force output resolution of 12 bits, position resolution of 0.001 inches, and a passive friction of less than 1% of the maximum force output – the maximum force output and the range of motion is application dependent. Other requirements include a system bandwidth of less than 50 Hz, a minimum sampling rate of 2 KHz, and a maximum latency of 1 millisecond. Currently, only few devices meet all these requirements among which is the PHANToM device. As a matter of fact, the hardware limitations such as the sensor's accuracy and the actuator's performance, constrain the fidelity with which haptic interactions can be simulated.

2.3 Computer haptics

Computer haptics comprises two main components, namely haptic rendering and visual rendering, to compute the virtual environment's graphics, sound, and force responses toward the human user. Haptic rendering – considered as the core of any haptic-based application – 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 group of algorithms and techniques to compute the virtual environment's graphics using mathematical expressions or a model.

2.3.1 Haptic rendering

Haptic rendering comprises three components: collision detection, force response, and control algorithms. Collision detection is the task of determining over time whether any points of two given objects, which may have different representations in the virtual environment, occupy the same location in space simultaneously. Force response algorithms are fired after a collision is detected to compute the ideal interaction force between the colliding avatars. These ideal forces cannot be applied as-is due to the haptic device software and hardware limitations, therefore, control algorithms command the haptic device in such a way to minimise the error between the ideal and applicable forces.

Collision-detection algorithms detect collisions between avatars and yield information about where, when, and ideally to what extent collisions (penetrations, indentations, contact areas, and so on) have occurred. The techniques for collision detection between primitives vary widely according to the representation of the objects and the information needed by the application. These algorithms are classified into five categories:

- static intersection tests
- moving intersection tests and continuous collision detection
- proximity queries and penetration depth
- ray-primitive tests and regular height fields
- primitives as Bounding Volumes.

For descriptions and surveys of these techniques as well as the algorithms that have been developed, please see Krishnan et al. (1998) and Lin and Manocha (2003).

The force response algorithms are classified into: geometry-dependent or surface-dependent algorithms. The geometric-dependent force rendering algorithms involve creating the force interactions when touching a frictionless and texture-less object, whereas surface-dependent algorithms render virtual objects' haptic textures and friction properties. Furthermore, the geometry-dependent algorithms are subcategorised according to the number of DOF necessary to describe the interaction force being rendered (1-DOF, 2-DOF, 3-DOF, etc.).

The objectives of control architectures are to improve the transparency of the device by decreasing the inertia felt by the user in an unconstrained movement. Essentially, they compute the transfer function that relates the force exerted by the user to the displacement of the haptic interface. The classification of these strategies is made in accordance with the interface inertia and the compensation method:

- impedance interaction
- impedance interaction with feed-forward compensation
- impedance interaction with positive feedback compensation
- impedance interaction with hybrid compensation
- impedance interaction with admittance compensation
- admittance interaction and compensation.

A brief description of these strategies has been presented in Gil and Sánchez (2005).

2.3.2 Visual and physical modelling

Object models have primarily been simple geometries such as planes, cylinders, spheres, and other basic shapes. The representational methods have witnessed different advantages and disadvantages according to the nature of the application. The most popular methodologies are:

- *Polygonal*. This is a classic representational form in 3D graphics. An object is represented by a mesh of polygonal facets.
- *Bi-cubic Parametric Patches*. A bicubic parametric patch is a curvilinear quadrilateral. It has four corner points joined by four edges that are themselves cubic curves.
- *Constructive Solid Geometry (CSG)*. These objects are usually parts that will be manufactured by casting, matching, or extruding and they can be built up in a CAD program by using simple elementary objects called geometry primitives.
- *Spatial Subdivision Technique*. These methods consider the entire object space and label each point in the space according to the object occupancy.
- *Implicit Representation*. Representing a whole object by a single implicit function is restricted to certain objects such as spheres.

Many techniques, which have been used in computer graphics for modelling rigid and deformable objects, range from modelling the contact forces and interactions of rigid objects to the geometry-based or physics-based deformable objects modelling. The most commonly used approaches for modelling the interactions that occur between rigid bodies that are in contact are penalty methods, analytic methods, and impulse methods. Moreover, deformable objects modelling research can be organised by techniques rather than applications and this comprises two classes: geometric-based and physical-based approaches. Geometric approaches provide a unified mathematical basis for representing analytical shapes and free-form entities represented as geometric primitives. The physical-based category is subdivided into four models: mass-spring models, finite element models, approximate continuum models, and a low degree of freedom models. Surveys for rigid and deformable objects modelling within the computer graphics research community are presented in Gibson and Mirtich (1997) and Requicha (1980) respectively.

2.4 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 is to bring the sense of 'touch' into multimedia applications and systems. 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 and/or coordination of this knowledge with other sensory displays such as audio, video, and text in a multimedia system."

2.4.1 Touch as the new media

In addition to traditional multimedia such as image, audio, and video, haptic – as a new media – plays a prominent role in making real-world objects physically palpable in a collaborative and/or shared virtual environment. The sensing of forces is tightly coupled with both the visual system and one's spatial sense; the eyes and hands work collectively to explore and manipulate objects. Moreover, researchers have demonstrated that haptic modality reduces the perceived musculoskeletal loading that is measured through pain and discomfort in completing a task (Dennerlein and Yang, 2001). Therefore, there is a trend in the design of interfaces towards multimodal human-computer interaction that incorporates the sense of touch.

2.4.2 Collaborative Haptic Audio Visual Environment (C-HAVE)

Traditionally, the implementation of a shared virtual simulation is limited by two problems: latency and coherency in manipulation. Delays in processing haptic information can easily bring the haptic interface to a state of instability. Therefore, many researches have been conducted to reduce delays and jitters in processing and transmitting force information over large distances. Various techniques were developed to integrate force feedback in shared virtual simulations, which are: dealing with significant and unpredictable delays, haptic information representation, synchronisation, haptic APIs, existing haptic software frameworks such as Reachin and Novint e-Touch, and haptic programming toolkits.

C-HAVE allow multiple users, each with his/her own haptic interface, to collaboratively and/or remotely manipulate shared objects in a virtual environment. A generic architecture that supports collaborative touch in virtual environments is introduced in Shen et al. (2003, 2004). The proposed architecture is implemented over the IEEE standard for distributed simulations and modelling (High Level Architecture/Real Time Infrastructure) to enable users to participate in the collaboration using different kinds of haptic devices. Recently, Boukerche et al. (2006) proposed a predictive technique for haptic collaboration to solve the problem of simulation lag in networked virtual environments. The authors developed a prototype application where two remote users carry a virtual box to a predefined target. The results, as the authors claimed, indicated that the proposed algorithm improved the quality of collaboration between remote users over a lossy network.

3 Haptics applications

Haptic research and development has been 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 (GUI's), games, multimedia publishing, scientific discovery and visualisation, arts and creation, editing sound and images, the vehicle industry, engineering, manufacturing, Tele-robotics and Tele-operations, education and training, as well as medical simulation and rehabilitation.

Therefore, the application's spectrum is quite vast and its trend of expansion is promising to increase. However, haptics interfaces are not yet ready to become a regular device, as the computer is today, in our environment. These interfaces confront computational challenges that become considerably more demanding, as the realistic experience has to result from the collaboration of two processes: one is coordinating the visual system, and the other is tracking the position and updating the forces on the haptic device that can be delivered or simulated.

3.1 Data visualisation

Traditionally, data visualisation uses animations or interactive graphics to analyse or solve a scientific problem. Incorporating haptics into scientific visualisation allows users to form a high-level view of their data more quickly and accurately.

3.1.1 Scientific data visualisation

At the University of Utah, researchers have developed a problem-solving environment for scientific computing called SCIRun (Durbeck et al., 1998a). Both haptics and graphics displays operate together in a common visualisation and are directed by the movement of the PHANToM (class 1.5) stylus. The haptic/graphic display is used to display flow and vector fields such as fluid flow models for airplane wings (Durbeck et al., 1998b). Similar systems have been developed for computational steering (Parker et al., 2000) and geoscientific applications (Veldkamp et al., 1998).

Green and Salisbury (1997) have produced a convincing soil simulation in which they have varied parameters such as soil properties, plow blade geometry, and the angle of attack. Haptics has also been incorporated into biomolecular simulation. For instance, Stone et al. (2001) proposed a system – called Interactive Molecular Dynamics (IMD) – that allows the manipulation of molecules in a molecular dynamic simulation with real-time force feedback and a graphical display. Furthermore, researchers at the Interactive Simulations Company introduced a haptic feedback component to sculpt, a program for analysing chemical and biological molecular structures, which will permit the analysis of molecular conformational flexibility and interactive docking. At the University of North Carolina, 6-DOF PHANToM devices have been used for haptic rendering of high-dimensional scientific datasets, including 3D force fields and tetrahedralised human head volume datasets.

3.1.2 Blind and visually impaired

In the last decade, a lot of research activities have been carried out for building applications and systems for blind and visually impaired people in his work, Levesque, (2005) presents a comprehensive survey of the use of haptics with the blind. A dual point haptic interface within the EU GRAB project has been developed for testing three applications: exploration of chart data, a city map explorer, and a simple adventure game (Avizzano et al., 2003). These applications were developed and demonstrated in a subsequent work (Iglesias et al., 2004). The applications were tested by visually impaired persons with different profiles, e.g., congenitally blind and acquired blindness, to confirm the validity and potential of the developed system. A multimodal tool has been developed to enable blind people to create and manipulate virtual graphs independently and receive haptic-based information at home via the Web.

Haptics have also been applied to mobility training. In van Scoy et al. (1999), the authors proposed a system that provides visually impaired persons with information about the site to be visited (such as business name, types and locations of doors, and types of traffic control devices). A real city block and its buildings could be explored with the PHANToM, using models of the buildings created from digital photographs of the scene from the streets. A similar work has also been proposed in Lecuyer et al. (2003).

3.2 Medical simulation and rehabilitation

The medical area has been an abundant source of haptic development. Introducing haptic exploration as the media of training has revolutionised many surgical procedures over the last few decades. Surgeons used to rely more on the feeling of net forces resulting from tool-tissue interactions and needed more training to successfully operate on patients.

3.2.1 Surgical simulation

Current simulations of biological tissues in surgical procedures are mostly, if not completely, visual in the cutting aspect. Force display for surgical procedures is classified as either internal or external forces. Internal forces are forces exerted between the thumb and finger whereas external forces are displayed by typical devices. Chial et al. (2002) presented a haptic scissors system intended to simulate the interface of a pair of Metzenbaum surgical scissors. It has been tested and compared against real tissue simulations. The haptic recording results from this project provide good guidelines for a detailed analysis for reality-based modelling, but there is still further research work to do to overcome the limitations in the presented approach.

Surgical simulators potentially address many of the issues in surgical training:

- they can generate scenarios of graduated complexity
- new and complex procedures can be practiced on a simulator before proceeding to a patient or animal
- students can practice on their own schedule and repeat the practice sessions as many times as they want.

Surgical simulators have been surveyed in Liu et al. (2003) and can be classified, according to their simulation complexity, as needle-based, Minimally Invasive Surgery (MIS), and open surgery.

The needle-based procedures use needles, catheters, guide-wires, and other small bore instruments for teaching relatively straightforward procedures with well-defined algorithms and are performed most commonly in abdominal surgery. The needle insertion action is sometimes difficult to perform and requires a programmed strategy. A novel interactive haptic approach is presented in DiMaio and Salcudean (2002) to simulate this procedure. The virtual needle insertions are simulated using a numerical material model and the needle shaft force distribution that has been derived. A virtual needle is advanced into a linear elastostatic model in two dimensions that are discretised using Finite Element Method. Other needle-based simulators can be found in Liu et al. (2001) and Ursino et al. (1999).

Minimally Invasive Surgery uses specially designed instruments that are introduced into the body via small incisions – commonly referred to as laparoscopic surgery. They are characterised by a limited range of motion and haptic feedback, the use of specialised tools, and video displays. Many laparoscopic simulators have been developed so far (Liu et al., 2005; Bhasin et al., 2005). For instance, a training set to simulate laparoscopic procedures based on virtual surgical instruments for deforming and cutting 3D anatomical models has been developed at INRIA (Picinbono et al., 2002). Another framework that includes many important aspects of haptics in Minimally Invasive Simulation and Training (MISST) is described in Basdogan et al. (2004). Several challenges have been uncovered in the design of MIS simulators including the haptic interface hardware design, tissue and organ model development, tool-tissue interactions, real-time graphical and haptic rendering, and recording and playback.

Open surgery requires direct visual and tactile contact with a region of interest in the body. The visual field, the range of haptic feedback, and the freedom of motion are considerably larger compared to MIS, thus it is more difficult to simulate. A biopsy is a practice of medicine that relies on the manual skills of the medical surgeons. Acquisition of these skills requires significant experience. One method has been proposed by Marti et al. (2003) to acquire such experience through a technique that combines visualisation with haptic rendering to provide real-time assistance to medical gestures. This biopsy navigator is a system that provides haptic feedback to the surgeon using patient specific data. Realistic open surgery simulation requires considerable advances in haptics and visual rendering, real-time deformation, and organ and tissue modelling.

3.2.2 Tele-surgery

In addition to problems associated with surgical simulation, Tele-surgery involves two additional issues: the coherency of the virtual scenes among all participating users, and force feedback stability when haptic information is sent over non-dedicated channels such as the internet where there is, among others latency and jitter. A Tele-surgery system comprises three components:

- a master console that includes input devices (surgeon side)
- a communication channel for bilateral control
- a slave robot (patient side).

To meet the above mentioned requirements, Gosselin et al. (2005) developed a new force feedback master arm that pays particular attention to precise manipulation and transparent behaviour. The proposed system provides two-hand manipulation (controls two slave devices simultaneously) and dexterous manipulation (movements as in open surgery). Furthermore, the input devices are statically balanced to avoid involuntary movements so that a high level of safety is guaranteed.

Collaborative haptic simulation architecture for tracheotomy surgery has been proposed in Zhou et al. (2004). Two application scenarios were considered: two doctors at geographically different places collaborating to perform an operation, and a trainer who coaches the trainee on how to perform a surgery in a Tele-mentory manner. The authors claim that the use of a haptic real-time controller (named HRTC) guarantees a stable haptic control loop and can compensate for network delays.

At the University of Ottawa, Georganas et al. developed a hapto-visual eye cataract surgery training application (El-Far et al., 2005; Hamam et al., 2006). The application supports three scenarios:

- an instructor and a trainee – in distinct physical locations – interacting in real-time in a Tele-mentor fashion
- a trainee learning the surgical procedure by means of perceptual cues
- a trainee performing the surgery without any guidance.

The developed application utilises the CANARIE network to ensure a smooth and transparent run of the remote components.

3.2.3 *Rehabilitation*

The rehabilitation process involves applying certain forces to the injured/disabled organ (such as the finger, arm, 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.

There have been many researches performed in which haptic interfaces are used for medical training and rehabilitation. For instance, Broeren at al. (2002) proposes using a 3D-computer game as a training utility to promote motor relearning in a patient suffering from a left arm paresis. The effectiveness of haptically guided Errorless Learning (EL) has also been tested in Connor et al. (2002) with a group of 12 patients with post-stroke visuoperceptual deficits. It has been shown that the concept of using EL with haptic feedback benefited some patients, but not all. Mali and Munih (2006) developed a low cost haptic device with two active DOF and with a tendon-driven transmission system optimised for finger exercises. The device was constructed to envelop a finger workspace and to generate forces up to 10 N.

Another haptic-based rehabilitation system for stroke patients is proposed in Shakra et al. (2006). The system can be set in the patient's house to provide a treatment that is not restricted by time and/or facilities to offer continuous evaluation of the patient's improvement. The proposed framework incorporated tests that occupational therapists have been using for a long time such as the Jebsen Hand and the Box and Block test.

A rehabilitation environment has been developed in Boian et al. (2003) using the 'Rutgers Ankle' haptic device that is used as a foot joystick. Variations in the exercises can be achieved by changing the impedance and stiffness levels and vibrations. The same

Rutgers Ankle interface has been used in the rehabilitation of musculoskeletal injuries (Deutsch et al., 2001). Another distributed collaborative environment is developed in McLaughlin et al. (2006) that include haptic sensory feedback augmented with a voice conferencing system to serve stroke patients in the sub-acute phase. Other applications include the rehabilitation of patients with hemispatial neglect (Baheux et al., 2004), hand rehabilitation (Burdea et al., 1997), PC-based orthopaedic rehabilitation (Popescu et al., 2000), upper limb rehabilitation (Lee et al., 2005), and robotic therapy using Hidden Markov Model (HMM) based skill learning (Yu et al., 2004).

3.2.4 Medical training

Simulation environments that utilise force feedback technologies can support medical education and training. The application of a desktop haptic interface in the pre-operative planning of the open surgery procedure used for training hip arthroplasty surgeons is introduced in Tsagarakis and Caldwell (2005). Another haptic-based medical training system is introduced in Abolmaesumi et al. (2004). The system allows trainees to visualise a virtual patient's anatomy simultaneously from any desired orientation and location. Medical training for the skill of bone drilling is investigated in Esen et al. (2004). It was observed that enabling haptic and acoustic feedback increases the performance of the trainees and it accelerates the skill training process. A haptic handwriting aid interface that stimulates re-learning the skill of writing after a stroke, or hand/eye coordination in writing, is presented in Mullins et al. (2005).

Langrana et al. (1997) used the Rutgers Master II haptic device in a training simulation for the palpation of subsurface liver tumours. The tumours are modelled as harder spheres within larger and softer spheres. The Finite Element Method (FEM) was used to calculate the reaction forces that correspond to the deformation obtained from force/deflection curves. Subsequent work Alhalabi et al. (2005) investigated the use of the HIRO interface (Kawasaki et al., 2003) to develop a medical simulator for palpation training in the detection of subsurface tumours. A physical-based model using FEM was used to simulate a real breast with subsurface tumours.

Researchers at Novint Technologies have developed a dental training simulator (Aviles and Ranta, 1999). They employ a PHANToM with four tips that mimic dental instruments to explore simulated materials like hard tooth enamel or dentin. Surgeons from the Pennsylvania State University's School of Medicine and the Cambridge-based Boston Dynamics developed a training simulation using two PHANToM interfaces. Medical residents pass simulated needles through blood vessels to collect baseline data on the surgical skill of new trainees. Many other medical education and training systems were proposed including a computer-based system for training laparoscopic procedures (Basdogan et al., 2001) and a Munich Knee Joint Simulator (Riener et al., 2004), among others.

Boulanger et al. (2006) developed a shared hapto-visual-audio-virtual environment (HAVE) with advanced multipoint video conferencing and distributed latency-compensated haptic technologies for collaborative medical research and training in Ophthalmology. Using this environment, trainers can remotely learn – in real-time – how to perform cataract operations from real operations that are performed by teaching surgeons.

3.3 E-commerce

Force feedback allows 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 instance, Shen et al. (2003) proposes a scenario for the online experience of buying a car. A virtual car showroom is created along with avatars for both the customer and the salesperson so that they can communicate in real-time. Furthermore, the customer avatar can perform haptic-based functions inside the car such as turn the ignition and the sound system on/off. The same scenario was developed in El-Far et al. (2004) within a generic framework called Unison. The framework serves to standardise the development of hapto-visual applications by providing a fixed set of services regardless of the choice of graphic or haptic software and hardware.

Another e-commerce application is introduced in Choi et al. (2003) and is realised based on the proposed mouse system to provide a more realistic interaction. The authors present a scenario where a customer logs onto a virtual sweater shop website and clicks on their favourite fabric. The gesture information associated with the fabric is downloaded and displayed on the local computer via the haptic mouse system. In this application, there is no need for real-time interaction yet the correctness of the haptic modelling is still an open issue.

3.4 Education

There has been a growing interest in developing haptic interfaces that 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 (Nilsen et al., 2004). The proposed system allows a haptic 3D representation of a geometry problem's construction and solution. The performance evaluation showed that the system is user friendly and has provided a more efficient learning approach. A new e-learning framework that combines the micro-world style Interactive Learning Environment (ILE) and virtual reality concepts is proposed in Inoue et al. (2005). The haptic device manipulates the virtual laboratory of the pulley in physics in a more intuitive and direct manner.

A system for constructing a haptic model of a mathematical function using PHANToM was introduced and partially implemented in van Scoy et al. (2000). The program accepts a mathematical function with one variable as input and constructs a haptic model made of balsa wood with the trace of the function carved into its surface. This prototype has been extended in van Scoy et al. (2001) to add a display of functions of two variables, sonification of functions of one variable, and improvements of the user interfaces. Another application that simulates a catapult has been developed to enable users to interact with the laws of physics by utilising a Force Feedback Slider (FFS) interface (Kretz et al., 2005). The FFS is a motorised potentiometer limited to 1D of movement (push/pull along a line) through which the user grabs the slider and moves the handle. It is claimed that the force feedback helps users in creating a mental model to understand the laws of physics.

3.5 Entertainment

Haptic research in the realm of home entertainment and computer games has blossomed during the past few years. According to Nilsen et al. (2004), the game experience comprises of four 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.

Vibration feedback joysticks are widely used input devices in current games. Early work on haptic joysticks (started at MIT and UNC (Minsky et al., 1990)) resulted in a 3-DOF device that simulates an object's inertia and surface texture. Using this device, Ouhyoung et al. (1995) designed a game-like flight simulator that makes the user feel the vibration whenever the aircraft is attacked by the enemy or he/she feels a reaction force on the handle whenever one shoots. Meanwhile, other research projects – such as HandJive (Fogg et al., 1998), Bed environment (Dodge, 1997), and Billow (Rueb et al., 1997) – began incorporating haptic feedback into interpersonal communication devices. Both Bed environment and Billow combined tactile input with auditory and visual media, however; HandJive is a haptic-only interface.

Subsequent research has introduced complex haptic-based games. For instance, the haptic battle pong (Morris and Joshi, 2004) is an extension to the pong with haptic controls using the Phantom device. The Phantom is used to position and orient the paddle while force feedback and 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 bricks in a wall with a ball and feels the rebound of the impact (Faust and Yoo, 2006). It has been shown that playing the haptic version is more fun yet the vibration feedback is not realistic. The use of haptic interfaces to manipulate digital media has also been investigated (Snibbe et al., 2001).

3.6 Arts and designs

Haptic communication opens new opportunities for virtual sculpturing and modelling, painting, and museums. Sculpturing and modelling arts are innately tactile and therefore the introduction of touch in virtual sculpturing 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 feeling" of the artistic process (Baxter et al., 2001). Finally, haptic modality is a significant asset for virtual art exhibitions as it allows an appreciation of 3D art pieces without jeopardising the conservation standards.

Adding force feedback to virtual sculpturing is a natural evolution to improve the immersion of the user and the perception of artworks. Virtual haptic sculpting, based on the constructive volume methodology, has been developed by Chen and Sun (2002) to perform melting, burning, stamping, painting, constructing and peeling interactions, in real-time. The authors in Dachille et al. (1999) had the vision that by using haptics in a virtual design environment, designers will be able to feel and deform the objects in a much more natural 3D setting. A sculpting system was proposed to allow users to interactively feel the physically realistic presence of virtual B-Spline objects with force feedback throughout the design process. Another volumetric sculpting system has been proposed to incorporate force feedback in a virtual sculpture system (Blanch et al., 2004).

Additionally, the authors proposed a solution for reducing the classical problems of instabilities during the interaction.

Virtual Clay is another example of using haptics to enhance the functionality of deformable models in a natural and intuitive way (McDonnell et al., 2001). The idea is that there is a natural connection between the two because both haptic and dynamic models depend on real-world physical laws to drive the realistic simulation and interaction of dynamic objects. Therefore, the toolkit is generated based on the dynamic subdivision solids that respond to applied forces in a natural and predictive manner and give the user the illusion of manipulating semi-elastic virtual clay.

In the art of painting, DAB is an interactive haptic painting interface that uses a novel deformable 3D brush model to give users natural control of complex brush strokes (Baxter et al., 2001). It was found that the force feedback enhances the sense of realism and provides tactile cues that help users in handling the paintbrush in a more sophisticated manner. The physical feeling of digital painting, derived from the Japanese traditional streaming art of Sumi-Nagashi, has been developed in Yoshida et al. (2004). Another haptic device, called the haptic desktop system, is used in a drawing task and acts as a virtual guide through its force feedback capabilities (Portillo et al., 2005).

Haptic technology has significant benefits for virtual museums (Brewster, 2001). It makes very fragile objects available to scholars, allows remote visitors to feel objects at a distance, lets blind people feel the exhibits, and allows museums to display a range of artifacts without taking up museum space. Bergamasco et al. (2002) are undertaking the architecture for the “Museum of Pure Form” virtual reality system. Two realisations have been developed:

- a system placed inside several museums and art galleries in a network of European cultural institutions that is made available to people visiting such institutions
- placing and testing the system inside a CAVE environment.

3.7 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. Modelling the sound produced when objects collide is the objective of a haptic interface that intends to provide more realism to feel a fabric’s surface roughness, friction, and softness (Huang et al., 2003). By using a rigid stylus as the medium to perceive and measure the fabric surface properties, Huang et al. (2003) presents a method to build an audio-haptic interface, such that 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.

4 Challenges in haptic technologies

Current haptic technology suffers from a number of limitations ranging from the high price and weight/size of the haptic interfaces to the limitations in workspace and the lack of force feedback to the body. Also, not to be ignored, are the high bandwidth, low network latency, high stability, and synchronisation requirements of haptics that are not met by the current state-of-the-art. A good review of the technical challenges of haptic interface technology can be found in Burdea (2000). In this section, we highlight and analyse various challenges in current haptic feedback technology.

4.1 Large haptic interface weight/size

One of the major shortcomings of wearable haptic interfaces is their large weight and/or size. For instance, the CyberGrasp with about 400 g weight is considered tiring for a user during lengthy simulations. Furthermore, even though the CyberPack allows for mobile force-feedback capability while wearing the CyberGrasp, it also increases the weight that users have to carry. One possible solution to address the weight problem would be the use of actuators that have much larger output power at a much lower mass (for example, the Rutgers Master II-ND). Unfortunately, this causes a decrease in the bandwidth and in the hand workspace that may be problematic in certain applications. Another solution, proposed by McNeely (1993), involves the use of a robot to move a turret called the "shape approximation device". The user wears a passive position measuring exoskeleton, while the robot changes its configuration to present contact surface information. The limitations for this solution are again cost and safety.

4.2 Bandwidth limitations

One of the constant challenges in haptic 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. A solution could be to embed computing in all haptic interfaces for the compression and analysis of haptic data, which reduces the bandwidth requirements especially for real-time distributed haptic applications. For more information about haptic data analysis and compression, the reader is referred to Ortega (2001) and Hinterseer et al. (2006).

4.3 Latency and Jitter

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 like an excessive rebound or vibration of reaction forces. Latency has two components: haptic rendering latency and network latency. Computational latency may slow down the update rates due to, for instance, the extreme computation time required by the real-time rendering of deformable objects. Network delays are usually induced by network congestion and bandwidth limitations in a distributed system.

Many solutions for computational latency and haptic fidelity in bitmapped virtual environments have been proposed; examples of such solutions can be found in Floyd (1999) and Balaniuk (1999). On the other hand, several researchers have investigated the influences of network issues on the haptic collaboration quality in shared virtual environments. For instance, Matsumoto et al. (2000) conducted a study of a multi-user environment with force feedback and found that the performance of the PHANToM is sensitive to network delays, and that their Sharing Contact Entity's State (SCES) solution demonstrated a good performance, as compared to taking no countermeasure against delay. Furthermore, the effects of varying the amount of simulated delays on the performance of a simple collaborative haptic task have been investigated in Allison et al. (2004). It was found that increasing the amount of simulated delays resulted in an increase in performance, either in errors in completing the task or in increasing the completion time. Even with the current efforts, network and computation latency continue to be a challenge.

4.4 Interoperability of haptic interfaces

Nowadays, 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.

The idea of having a framework that facilitates the development of haptic applications was introduced by the authors in El-Far et al. (2004), who proposed a viable and extensible framework called Unison to standardise the development process of hapto-visual applications. The framework classifies different components in groups of generic standards and reusable services that require plug-ins to interface the component with the framework. The limitation is that the interface must be hard coded into a plug-in before a component becomes usable by the framework. Subsequently, Orozco et al. (2005) presented an adaptive context-aware haptic framework to support a diversity of applications. The framework is capable of learning about the user's behaviour and is adaptable to different application requirements. Using specific pattern recognition methodologies, the framework dictates what device to use and how to use it, and it directs the user to the appropriate environment.

Only recently, a description language called Haptic Applications Meta Language (HAML) has been introduced in Zhou et al. (2005) and El-Far et al. (2006) to standardise the description of haptic application components (such as haptic API, virtual environment, haptic device drivers, etc.) as a step towards automating the composition of haptic applications. The advantage of this approach is that once the description for a component is generated, it can be reused and integrated into the framework, thus making the inclusion of any haptic application component a 'Plug and Play' task. Subsequently, a HAML-based framework that can automatically manufacture a haptic-based virtual environment application was described in Eid et al. (2006). The authors have shown how to abstractly interface with different haptic APIs through the use of Microsoft .NET wrappers.

4.5 Instability and vibration

While update rates of 30 Hz are fast enough for graphics rendering, haptic update rates needs to be approximately 1,000 Hz. If update rates fall below that value, the haptic device becomes unstable and vibrates when in contact with virtual hard surfaces. Algorithms developed so far Gregory et al. (1999) have solved the problem of a probe point colliding with virtual objects, but this is clearly not sufficient as the feeling of one 3D object moving in to contact with another object is to be displayed in a realistic manner. One possible solution to this problem could be to perform the haptic and graphic upgrades by two independent threads (Luciano et al., 2003). One device communicates with the device retrieving its current position and orientation, and sends forces to be applied to the haptic device in one thread, while another class renders the scene graph in another thread.

4.6 Haptic rendering computation cost

Particularly, collision detection is a major research challenge in real time virtual reality based simulations, especially when haptic feedback is required. The computational cost of the algorithm depends not only on the complexity of the basic interference test and object modelling, but on the number of times this test is performed. Several strategies have been developed to apply these tests at the time and place where a collision can truly occur. These strategies rely on distance computation algorithms, hierarchical object representations, orientation-based pruning criteria, and space portioning schemes.

4.7 Other challenges

Other research challenges include limitations in collision detection algorithms, realistic object modelling, and synchronisation. Collision detection is a major research challenge in real time virtual reality based simulations especially when haptic feedback is required. The computational cost of the algorithm depends not only on the complexity of the basic interference test and object modelling, but on the number of times this test is performed. As for object modelling, the challenge is to verify the accuracy of the computer simulation, to compare between simulation and reality, and to refine the various models for deformable objects. Moreover, modelling compliant objects, such as for surgical simulation and training, presents many challenging problems to enable realistic deformations, arbitrary collisions, and topological changes caused by cutting and joining actions. Finally, synchronisation of the visual, auditory, and haptic displays can be problematic because each modality requires different types of approximations to simulate the same physical phenomenon (Srinivasan and Basdogan, 1997).

5 Summary and conclusions

This work covers both historically significant and recent work relevant to haptic technologies and applications. This includes an in-depth look at the terminology of human, machine, computer, and multimedia haptics and provides a comprehensive overview of recent work performed in haptics applications. Afterward, we presented some of the research questions, problems and challenges that may be of interest to researchers in the haptic community. In the following, we present some of our observations as well as recommendations for future research in haptic technologies.

First of all, it is worth mentioning that even with the significant progress in haptic technologies, the incorporation of haptics into virtual environments is still in its infancy. A wide range of human activities, including communication, education, art, entertainment, commerce, and science, would forever change if we learn how to capture, manipulate, and create haptic sensory stimuli that are nearly indistinguishable from reality. For the field to move beyond today's state of the art, many commercial and technological barriers are to be surmounted. First, business models/frameworks are needed to make haptic devices practical, inexpensive, and widely accessible with the ultimate goal is to make a haptic device as easily pluggable as the mouse in a computer.

Moreover, multipoint, multihand, and multiperson interaction scenarios need further investigations to reach enticingly rich interactivity. Finally, we should not forget that touch and physical interaction are among the fundamental questions in haptic systems development. By rendering how objects feel through haptic technology, we communicate information that might reflect a desire to speak a physically-based language that has never been explored before.

From an application perspective, we envision many interesting applications where haptics technologies have significant potential. For instance, Biometric systems identify users based on their behaviour or physiological characteristics (Wayman, 2001). The potential of haptics technology is to continuously authenticate and control access to high security applications/systems for many reasons. Firstly, conventional security systems, which may be based on a password, token, or even a physical biometric, can only assure the presence of the correct person at the beginning of the session; it can not detect if a hacker takes over the control. Secondly, traditional authentication means such as a login ID and passwords can easily be compromised, whereas haptic-based biometric systems are significantly more difficult to compromise Orozco et al. (2006) and El Saddik et al. (2007).

Another interesting applications-enabling tool is the haptic playback. Haptic interfaces can be used to provide physical interaction with trainees; thus decreasing the trainees/trainer ratios. As an example, haptic playback could be useful in medical training where the motions of an expert may be recorded and saved for later ‘playback’ by a trainee (Basdogan et al., 2004). A haptic device is programmed to provide the same predefined trajectory and controlled forces for training the user’s motor-control skills. Despite the several haptic playback systems and prototypes that have been implemented and evaluated (Yan et al., 1999; Williams et al., 2004), haptics playback remains an example of uncharted territory in haptics research.

Another open research in haptics is the haptic data compression, fuelled by the demands for real-time simultaneous recording and transmission of voluminous data that are produced by multiple sensors (Shahabi et al., 2002). 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:

- development of a system for 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 lossy 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.

Last but not least, the use of wireless tactile sensing devices has recently 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 (Pai and Rizun, 2003). Many researchers have worked on the realisation of such devices such as (Pai and Rizun, 2003; Hakozaki and Oasa, 2000) though much work remains to be done in this fertile field. 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, integration with well-established wireless technologies such as Bluetooth, among others.

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