

Tutorial

Haptic interfaces and devices

Vincent Hayward
Oliver R. Astley
Manuel Cruz-Hernandez
Danny Grant and
Gabriel Robles-De-La-Torre

The authors

Vincent Hayward is based at Center for Intelligent Machines, McGill University, Montréal, Québec, Canada. **Oliver R. Astley** is based at GE Corporate Research and Development, Niskayuna, USA. **Manuel Cruz-Hernandez** and **Danny Grant** are based at Immersion Canada, Inc., Montréal, Québec, Canada. **Gabriel Robles-De-La-Torre** is based at Programa de Investigación en Matemáticas Aplicadas y, Computación, Instituto Mexicano del Petróleo, México City, México.

Keywords

Communications, Robotics, Sensors, User interfaces

Abstract

Haptic interfaces enable person-machine communication through touch, and most commonly, in response to user movements. We comment on a distinct property of haptic interfaces, that of providing for simultaneous information exchange between a user and a machine. We also comment on the fact that, like other kinds of displays, they can take advantage of both the strengths and the limitations of human perception. The paper then proceeds with a description of the components and the modus operandi of haptic interfaces, followed by a list of current and prospective applications and a discussion of a cross-section of current device designs.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0260-2288.htm

Sensor Review
Volume 24 · Number 1 · 2004 · pp. 16–29
© Emerald Group Publishing Limited · ISSN 0260-2288
DOI 10.1108/02602280410515770

1. Introduction

Before the widespread use of computers in the work place, almost all human tasks involved the use of exquisite sensory-motor skills. By and large, computer interfaces have not taken great advantage of these fundamental human capabilities. With the exception of input devices such as the mouse, computer interaction relies on skills similar to those needed for using typewriters. Haptic interfaces may be viewed as an approach to address this limitation. It is thus possible to classify haptics in the area of computer-human interfaces. Unlike traditional interfaces that provide visual and auditory information, haptic interfaces generate mechanical signals that stimulate human kinesthetic and touch channels. Haptic interfaces also provide humans with the means to act on their environment. We can therefore attempt to define haptic interfaces as being concerned with the association of gesture to touch and kinesthesia to provide for communication between the humans and machines.

The field is inherently multidisciplinary and borrows from many areas, including robotics, experimental psychology, biology, computer science, systems and control, and others. The field of haptics is also growing rapidly. At present, the number of published papers with the word “haptic” in them approaches a thousand a year, all disciplines included. Just 10 years back, there were only a few dozens.

The word “haptics” refers to the capability to sense a natural or synthetic mechanical environment through touch. Haptics also includes kinesthesia (or proprioception), the ability to perceive one’s body position, movement and weight. It has become common to speak of the “haptic channel” to collectively designate the sensory and motor components of haptics. This is because certain anatomical parts

This research was partly funded by IRIS, the Institute for Robotics and Intelligent Systems (Canada’s Network of Centers of Excellence) and by NSERC, the Natural Sciences and Engineering Council of Canada, in the form of an operating grant for the first author. The authors are former or were, members of the Haptics Laboratory of the Center for Intelligent Machines, McGill University, Montréal, Canada. They would like to thank Dr Ian Sinclair from MPB Technologies for helpful comments.



(in particular the hand) are unitary organs in which perceiving the world and acting upon it are activities that take place together. For example, grasping an unfamiliar object also involves exploring it actively with our hands. Tactile and kinesthetic channels work together to provide humans with means to perceive and act on their environment.

2. The function of haptic interfaces

The idea of using touch as a means of communication was popularized by Craig and Rollman (1999) and Sherrick (1985):

“Our understanding of how simple patterns combine to yield the complexity needed to increase channel capacity for continuous information streams is still primitive”.

It certainly still, is the case today.

It is possible to discuss the function of a haptic interface by considering, on the one hand, an input device such as a computer mouse, and on the other hand a sheet of paper, viewed as a display device. Consider first, a blank sheet of paper: it contains little information (barring being a sheet of paper). The sheet is intended to support the information coded in the form of structure and discontinuities laid out on it by means of ink to change its reflective properties. Next, consider a computer screen with graphics capabilities. It can be programmed pixel by pixel to display information, also using structured discontinuities. Analogously, a computer mouse (or any other conventional input device) contains little mechanically-encoded information (just a fixed weight, shape, and rubbing properties). It is not programmable. The step that was made to move from the sheet of paper to the graphics screen is analogous to the step made to move from a computer mouse to a haptic interface. Whereas the graphics screen can change its optical properties under computer control, a haptic device can change its mechanical properties under computer control. The ability to have programmable mechanical properties provides for a bidirectional exchange of energy, and therefore information, between the user and the outside world.

While the term “haptic display” is sometimes used, it is probably not the best suited because it emphasizes unidirectional information transfer

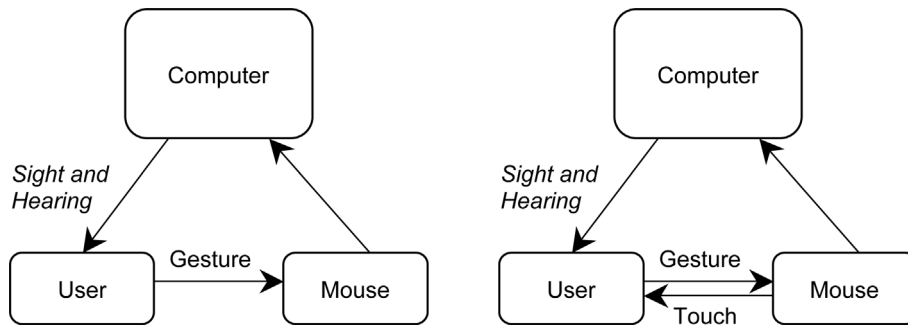
like that of typical “graphic displays” (such as cathode ray tubes) and “audio systems” (like high-fidelity music reproduction systems). This fundamental difference can be understood by considering Figure 1, in which a regular mouse is compared to a “haptically enabled” mouse with programmable mechanical properties. The arrows represent the direction of information flow. With a typical mouse, this is limited to a unidirectional input from the mouse to the computer. The user of a conventional mouse receives almost no information from its movements, although its friction and inertial properties may assist the user in performing skilful movements. The buttons on it are considerably richer: their mechanical detent and the small acoustical noise they produce inform the user that a discrete-state change has occurred. Nevertheless, the buttons are not programmable. The haptic mouse, on the other hand, can provide the user with programmable feedback based on the sense of touch, allowing a faster and more intuitive interaction with the machine.

In general, haptic interfaces attempt to make the information flow non-zero to the user, as in the example of moving from the blank sheet of paper to the graphics screen. This can be further explained from an information-theoretic view point: consider a channel in which x is the input and y is the output. In a lossless channel, the entropy of x given y , $H(x|y)$, is zero: the output uniquely specifies the input. In a useless channel $H(x|y) = H(x)$, the knowledge of the output says nothing about the input, x and y are independent. This is the case of ordinary input devices such as a mouse. They can be moved here and there, but the mechanical signals they produce are unrelated to the state of the machine; they are useless as a channel.

This distinction is also most apparent if one considers that visual, auditory, olfactory and vestibular signals can be recorded and replayed (people watch movies, listen to audio recordings, or have machine-controlled rides in vehicle simulators). On the other hand, recording and replaying kinesthetic and tactile sensations must involve user movement, except possibly for the display of vibro-tactile sensations.

All objects, natural or manufactured, fall into one of the two categories. They are inert or

Figure 1 A distinguishing feature of haptic interfaces is the simultaneous exchange of information between the user and the machine



active, roughly speaking, inanimate or animate. Inert objects can only dissipate mechanical energy, while active ones may supply some energy. Thus, there can be two kinds of haptic devices, conventionally termed passive or active, but they all share the property of being programmable.

Passive devices are often designed to have programmable dissipation, as a function of position or time. To this category belong the devices having controllable brakes. Another category of passive devices consists of those that rely on non-holonomic constraints (constraints involving velocity). Yet another possibility is to modify the elastic behavior of an element to become harder or softer. The programmability of passive devices comes from the possibility of modifying these constraints under computer control.

As for active devices, the energy exchange between a user and the machine is entirely a function of the feedback control which is applied. Then two categories arise: either the actuators act as a force source (a variable of effort), and position is measured, or the actuators act as a position source and then force is measured. The former case is termed isotonic (force does not change with position) while the latter is called isometric (position does not change with force). Closing the loop around an isotonic device corresponds to specifying an impedance to produce a simulation, and the other case corresponds to an admittance.

It is often desired that active devices be used to reproduce synthetic environments such that these environments are passive, for example to simulate a surgical act. How well this is achieved is, in fact, a particular challenge (Brown and

Colgate, 1997; Colgate and Schenkel, 1997; Hannaford and Ryu, 2002; Mahvash and Hayward, 2003; Miller *et al.*, 1999; Salisbury *et al.*, 1995). Conversely, the ability to create a temporally active simulation can be quite useful to increase the flow of information between the machine and the user. For example, simulating the behavior of the steering wheel of a race car requires the interaction to be active. Passive devices cannot create active simulations. Finally, it must be noticed that the possibility exists in unstable interactions with passive environments (a drum roll, for example) if the conditions are such that the user can supply the energy needed to sustain the oscillation.

To summarize, regardless of the approach to their design, bidirectionality is the single most distinguishing feature of haptic interfaces, when compared with other machine interfaces, and this observation explains in part why they create a strong sensation of immediacy. A haptic device must be designed to “read and write” from the human hand (or foot, or other body parts). This combined “read and write” property may explain why the first applications of this technology involved “fast-paced interactivity” (Section 3). As it turns out, the “read” part has been extensively explored, and a great many types of devices already exist (knobs, keys, joysticks, pointing devices, etc.). The “write” part is comparatively more difficult to achieve. More specifically, the function of the haptic interface is to recreate constitutive properties: relationships between variables of flow and effort. Haptic interfaces are concerned with the technical means needed to make use of the extensive and exquisite capabilities of human touch, including proprioception, motor control,

etc. (Subsections 4.1 and 4.2). To achieve this, they must be programmable devices capable of recreating mechanical phenomena of perceptual relevance and functional importance.

It is also important to recall that haptics, as a technological niche, inherits much from teleoperation, which can be considered as its mother discipline (Bejczy and Salisbury, 1980; Flateau *et al.*, 1973; Goertz, 1952, 1964; Vertut *et al.*, 1976). In a sense, haptics is like teleoperation, but the remote slave system is purely computational, i.e. “virtual”. The virtual aspect has been helped greatly by the tremendous progress in computing and telecommunications. Plainly speaking, one replaces the teleoperator slave by a computer, thereby creating the possibility of virtuality: the slave and the world are computational, and thereby can be imaginary, or not restricted by normal physical constraints (as a matter of fact, virtual reality simulations rarely are). Driven by this, haptics became an independent technological niche in the past decade.

There is another relationship to robotics. Haptic devices can be regarded as robots, however, as robots having a very special function or task, that of interacting with humans. This occurs mostly through the hand, but also via other anatomical regions, often, but not always, limbs and extremities. Thus, many “robotic problems” are relevant to haptic interfaces and vice versa.

3. Examples of applications

Graphical user interfaces (GUIs) have demonstrated that interactive presentation of data does not have to imitate reality, not even remotely. Being “suggestive” is what matters the most. Pull-down menus and scrolling slider bars cannot be found anywhere, but on computer screens; real paper file folders are not infinitely recursive, and so on. The same holds for haptic interfaces. For example, the interaction forces that we experience when moving objects occur when these objects contact one another (except with magnets and inertial effects). With haptics, we can perfectly suggest a relationship between two distinct objects by creating a mutual interaction force, even if they are visually presented as being disconnected.

Alternatively, some applications demand a significant amount of fidelity with respect to the actual tasks being recreated. In other words, haptic interfaces can be designed to provide for a literal reproduction of the phenomena that occur during actual manipulation. This is what is called “quest for realism” in computer graphics. The training of sensory-motor skills such as surgical abilities is one example in which the need for realism exists.

It is useful to keep these distinctions in mind while surveying the applications of haptic devices. An interesting aspect of this technology is that some applications are presently part of the commercial activities, good many of them at the precompetitive stage. For example, one of the earliest researched application of haptic interfaces was the layering of haptic cues on conventional graphical interfaces (Hannaford and Szakaly, 1989; Kelley and Salcudean, 1994; Ramstein and Hayward, 1994). Currently, this has reached the consumer arena.

In the following subsections, applications are surveyed in terms of activity areas. The research is now so intense that only a few references will be included.

3.1 Force-reflecting input devices for use with graphical user interfaces

As mentioned, one of the first researched applications of haptic interfaces was the enhancement of existing graphical user interfaces. Elements of these GUIs (windows, pushbuttons, pull-down menus, words of a text, drawings) can be rendered mechanically. Human factor studies indicate improvements in routine computer interactions in speed, precision, and reduction of fatigue (Keyson, 1996). More specifically, cases that benefit from the enhancement of designation tasks (point and click, dragging, snap-to and so on) include drawing packages, text editors, spreadsheets, hypertext navigation, and operating system interfaces. In the latter case, haptic cues can further be used to represent topological relationships in terms of importance: strength, recency, or urgency. Haptic cues may also be used to provide for interactive annotations. For example, haptic tabs can be inserted for efficient retrieval in large documents and databases by specific users. They can also provide for efficient multi-author document editing.

3.2 Games

Modes of interaction and the sense of user immersion are greatly enhanced by applying force feedback to the player. Dexterity games available earlier in fixed form can be made infinitely programmable: placing, balancing, hitting and bouncing. As well, many opportunities exist for educational games. It is possible to illustrate concepts in dynamics, kinematics, magnetism, waves, flows and many other physical phenomena, or in mathematics and anatomy. Other kinds of games include combinatorial mind games, puzzles, and guess games that include visual and mechanical constraints, as well as most situation games. In the latter case, force feedback is already at the commercial stage, to assist in driving, piloting, exploring, and so on.

3.3 Multi-media publishing

Current multi-media and hypertext applications include text, sound, images, and video. For lack of appropriate devices so far, haptics has been ignored as a medium of communication. One could envision “mechanical documents”. For example, a new form of document that would include movement which can be experienced visually (video), audibly (spatialization), and also haptically. This raises the question of authoring tools (such as Immersion Studio™) and their necessity for the design of haptic sensations. Material properties can also be conveyed. A frequently mentioned application of this capability is the creation of online catalogues with haptic feedback. These would however benefit greatly from the development of practical, distributed tactile displays, which are not yet available.

3.4 Scientific discovery

Data display was in fact one of the earliest applications of haptics, with the molecule docking project (Brooks *et al.*, 1990). Other display applications include: multi-dimensional maps, data mining in geology (or in related, applied fields such as oil and gas prospecting), remote sensing, and the display of fields and flows. An attractive property of haptics is the ability to convey the existence of small details, which typically clutter the graphical presentation of data, while minimizing the need

to zoom in and out. Projects exist to use haptics to enhance the human interface of imaging instruments such as scanning, tunneling, and atomic force microscopes (Falvo *et al.*, 1996).

3.5 Arts and creation

Musicians and visual artists are increasingly using computers. However, creators often prefer to use their hands as directly as possible (as in sketching). Haptic communication with computers opens completely new opportunities. In music, advances in real-time synthesis tools increase the demand for interactive controllers which are presently mostly confined to the existing MIDI fixed interfaces (Rovan and Hayward, 2000). In the graphic arts and design, especially the creation of animation, much activity is under way (O’Modhrain, 2000).

3.6 Editing sounds and images

Haptics can provide for rapid access, and browsing through sound and video documents for editing, splicing, and mixing (MacLean *et al.*, 1999).

3.7 Vehicle operation and control rooms

In stressful, and fast-paced environments, haptic communication can be used to alleviate visual load (Payette *et al.*, 1996). Haptic controllers are already commercially available in cars (iDrive™ equipped BMW 7 series and Rolls-Royce Phantom). With a single programmable rotary controller, users can navigate menus, scroll lists, control sliders, etc. by experiencing distinctive haptic sensations for each widget. In this fashion a single controller serves as the input for a multitude of functions, with the haptic feedback serving to make the interface more intuitive and natural to use. Similarly, applications are finding their way into control rooms (air traffic control, nuclear).

3.8 Engineering

In computer-aided design, designers can experience minute details with their hands, such as wanted or unwanted artefacts of a design which are cumbersome to display visually. Simulated structures can be manually tested, assessed and debugged (Nahvi *et al.*, 1998).

3.9 Manufacturing

In manufacturing, many opportunities exist. For example, haptics can assist design for assembly, in terms of reducing the need for prototyping, and as well as for rapid prototyping. It is also possible to assess human maintainability of complex systems before they are built (McNeely *et al.*, 1999). Programming of complex manufacturing devices such as multi-axis, numerically-controlled machines or robots can be facilitated.

3.10 Telerobotics and teleoperation

As commented earlier, teleoperation is the mother discipline. Haptic devices are used in supervisor control modes such as teleprogramming, predictive displays, etc. Teleoperation systems still have a need for high-quality manual controllers.

3.11 Education and training

Dangerous systems or systems with very limited availability (e.g. surgery patients) can be simulated using haptics for training purposes. Surgical training, in particular, is the subject of intense research (Delp *et al.*, 1997). Other opportunities include the training of sensory-motor skills in general.

3.12 Rehabilitation

Applications include the improvement of working conditions for visually impaired people, and better interfaces to alleviate motor system impairment (Bergamasco and Avizzano, 1997; Dufresne *et al.*, 1995; Krebs *et al.*, 1998).

3.13 Scientific study of touch

Last but not the least, the availability of haptic devices makes it possible to study the haptic channel in humans (and other species) in exciting and perhaps earlier impossible ways. Haptic devices allow the creation of special, computer-controlled stimuli which are used in studies that explore the sense of touch functions. This is analogous to the use of programmable sound cards and computer graphics in human hearing and vision studies (Hogan *et al.*, 1990; Robles-De-La-Torre and Hayward, 2000, 2001; Weisenberger *et al.*, 2000). In turn, the knowledge gained of the haptic function contributes to the development of new haptic interfaces and applications

(Basdogan and Srinivasan, 2002; Berthoz, 1996; Biggs and Srinivasan, 2002; Flanagan and Lederman, 2001).

4. Principle of operation

4.1 Tactile sensations and the kinesthetic sense

In general, tactile sensations include pressure, texture, puncture, thermal properties, softness, wetness, friction-induced phenomena such as slip, adhesion, and micro failures, as well as local features of objects such as shape, edges, embossings and recessed features. In addition, vibrotactile sensations refer to the perception of oscillating objects in contact with the skin. This is appreciated by attending to the sensations experienced while holding a sheet of paper where the three main functions of touch are used. The grade and texture of the paper are perceived by gently rubbing it (identify material), and its border is found by exploring the edges (identify shape). Speaking loudly near it causes vibro-tactile sensations to be experienced (rapid oscillations). This distinction appears to correspond to specific mechanoreceptors and neural codes (Craig and Rollman, 1999; Goodwin *et al.*, 1997; Johnson, 2001; Johnson and Hsiao, 1992; LaMotte and Srinivasan, 1991).

Several kinds of receptors have been found to mediate tactile sensation in the skin or in the subcutaneous tissues; consequently, it is customary to designate the skin as the seat of this sense (A very large organ, indeed; it covers roughly 2 m²; it weighs about 5 m²kg, its innervation is up to hundreds of receptors per square centimeter). The biophysical attributes of the skin vary tremendously with the parts of the body it covers. The tactile system occupies a great part of the afferent pathways of the peripheral nervous system, as well as a significant part of the central nervous system (Craig and Rollman, 1999; Darian-Smith, 1984).

Proprioceptive, or kinesthetic perception, refers to the awareness of one's body state, including position, velocity and forces supplied by the muscles through a variety of receptors located in the skin, joints, skeletal muscles, and tendons. Together, proprioception and tactile sensations are fundamental to manipulation and locomotion.

4.2 Human perception and haptic interfaces

When we watch a high-resolution digital movie, we do not perceive a series of still pictures that are presented in sequence, nor do we apprehend an array of colored pixels. Instead, we perceive a visual scene that is strikingly close to everyday visual experiences. This is possible because the temporal sensitivity of the human visual system is not sufficient to detect the fast presentation of the movie frames nor it can resolve individual pixels. This is an example of how the architecture and limitations of a perceptual system can be exploited to build engineering systems that elicit realistic, complex perceptual experiences. Examples of these systems include graphics screens, TV, tape recorders, audio synthesizers, flight simulators, and, not surprisingly, haptic interfaces.

The sense of touch differs from the visual system in that it requires update rates significantly higher than those needed to display video (1 kHz or more is required to satisfy the signal representation theorem and to minimize interaction delay). The physical interface that enables user-machine interaction can also have a great deal of variability. It is in general very difficult to produce perfectly “realistic” haptic interaction.

Fortunately, even while using an imperfect haptic device, a user quickly adapts to its interference, ignores its imperfections, and naturally associates the device’s mechanical stimulation to everyday experiences such as perceiving surface texture and shape of the objects through touch. Also, when haptic interfaces are combined with graphic displays, the user readily associates adequate haptic stimulation to a graphically displayed object. It is not unusual to perceive the haptic sensations as if they occurred at the graphic display itself. This happens even though what is seen and what is haptically felt may occur in completely different spatial locations (i.e. the haptic interface may be on a table alongside the graphic display where the objects are viewed).

However, if the imperfections in the haptic device are too obtrusive, the sense of haptic realism breaks down. This is analogous to what happens if a movie projector slows down to one frame per second: the movie turns into a series of stills. The quality of the illusory haptic

experience – as with any other technological devices – is a function of the interplay between the user’s perceptual system and the intrinsic technical qualities of the interfaces, such as dynamic range, resolution, and appropriateness of the signals being generated.

4.3 Components

A complete haptic interface usually includes one or several electromechanical transducers (sensors and actuators) in contact with a user in order to apply mechanical signals to distinct areas of the body, and to measure other mechanical signals at the same distinct areas of the body. Whether these signals should refer to forces, displacements, or a combination of these and their time derivatives, is still the object of debate.

Another important part of a complete interface is the computational system driving the transducers. The function of this computational system is to provide haptic rendering capabilities, which are analogous to the visual rendering functions of common graphic systems. Haptic rendering, however, stresses the bidirectional exchange of information between the interface and the user (Salisbury *et al.*, 1995). The computational task in haptic rendering is to generate signals that are relevant to a particular application. Several approaches exist for creating such haptic feedback. For example, a model may be used to represent an environment, and its equations solved computationally to find forces as a function of displacements and their derivatives (or vice versa). The model may be developed from first principles, or parameterized to represent only certain desired aspects (MacLean, 1996).

The characteristics of the human haptic system allow in some cases the use of simplified physical models to render haptic objects that compete in realism with actually physical objects (Flanagan and Lederman, 2001; Minsky, 1995; Morgenbesser and Srinivasan, 1996; Robles-De-La-Torre and Hayward, 2001). Another possibility is the recording of ground data and replaying it as a function of state variables and/or time (Okamura *et al.*, 2000). The computational task can range from the light (translation of a GUI into a force field) to the intractable (for example, objects

described by continuum mechanics). So many possibilities exist, that this should be the topic of a separate discussion. This computational task is usually mapped onto a data processing hierarchy consisting of several computing units and communication channels. The engineering problem is to map the computational task onto the computational hierarchy so that no constraint is violated in terms of update rates and data transfer rates. For a recent survey of haptic rendering, see Basdogan and Srinivasan (2002).

5. Devices: concepts and examples

In this section, we examine a cross-section of the existing devices selected to illustrate the diversity of design niches being explored and the vitality of the activity in this field (a complete survey would be much too long). We also comment on prominent features of these designs. Specific technical requirements of devices are reviewed in Hayward and Astley (1996). In this section, the description of entire families of haptic devices, completely passive devices, and foot contacting devices, and distributed tactile displays, unfortunately had to be omitted, despite significant activity in all these areas.

5.1 Programmable keyboard

One of the most documented examples of a multiple force-feedback implementation is the Clavier R troactif Modulaire, a project headed by Cadoz, which consists of a piano-like Lorentz-actuated keyboard providing computer-driven force feedback for each of its 16 keys (Cadoz *et al.*, 1990), and directed at musical creation research (Cadoz and Ramstein, 1990).

5.2 Exoskeletons

The exoskeleton devices developed by Bergamasco and co-workers incorporate many observations regarding the human biomechanics. To achieve wearability, the system uses a variety of techniques including motor remotizing, sophisticated cable routing, and friction reduction by feedback (Bergamasco *et al.*, 1992). Being worn, the device body interface is partly bracing and partly held.

Many other devices have been designed by this laboratory (see Figure 2 for recent developments).

5.3 Desktop scale

A six degree of freedom device is the result of the pioneering work of Iwata, who advocated the design of small devices. It adopts a ‘‘parallel platform’’ design supported by three gear-driven five bar linkages. The result is a compact and powerful table top design. The initial design is described by Iwata (1990); several versions have been developed thereafter.

5.4 Grasping

Howe (1992) designed a double, two degree of freedom apparatus intended for two-finger grasping studies. It uses direct-driven, parallel linkages resulting in a very wide dynamic range. The user’s fingers interact unilaterally with the device on the inner side of boxes, allowing precision grip.

5.5 Point interaction

The Phantom™ has become a popular device in research laboratories. There are several variants, but generally a stylus is grasped, or a thimble braces the user’s finger (Figure 3). There are three actuated degrees of freedom and three sensed orientations. A typical configuration has a work volume of 2.7 dm³. A key design aspect is a capstan drive which avoids the use of gears and makes it possible to amplify the torque of small DC motors with a concomitant increase of damping and inertia. The initial design is described in Massie and Salisbury (1994) and is commercially available.

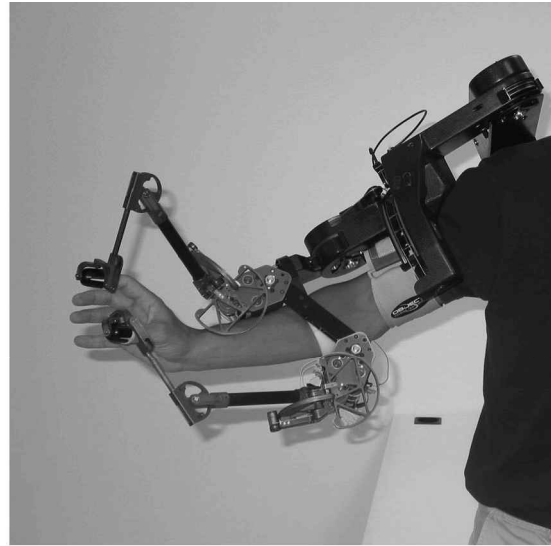
5.6 High power devices

Colgate and his group have created number of devices that were used for studies in control. One early design, described in Millman *et al.* (1993), features high power and bandwidth for tool use simulation. This group also investigates a number of designs in the family of passive devices. Other high power devices were developed by Ellis *et al.* (1993) and by Hannaford’s group (Adams *et al.*, 2001).

5.7 Augmented mice

An innovative system is described by Akamatsu *et al.* (1994). It has the general shape and

Figure 2 The PERCRO Laboratory (Scuola Superiore di studi Universitari S. Anna, Pisa, Italy) has extensive experience with the development of exoskeleton-type haptic interfaces



Note: The left panel shows such a device applied to the simulation of the driving experience for cockpit design optimization. The right panel shows a variant of this device accommodating two additional sub-devices able to simulate the manipulation of objects "out of thin air".

function of a computer mouse, but includes two haptic feedback features. One is an electromagnetic braking system which provides programmable dissipative friction forces, and the other is a transducer to provide vibro-tactile sensations.

5.8 Joystick

The force-feedback two degree of freedom joystick described by Adelstein and Rosen (1992) is one example of a device designed with specific performance figures in mind. Many other force-feedback joysticks were designed for various applications.

5.9 Separate carrier

Luecke *et al.* (1996) describe a design concept whereby individual high-fidelity and direct-driven force feedback devices act on the fingers of the hand and are moved about by a large workspace stiff robotic carrier.

5.10 Horizontal planar workspace

The Pantograph (Hayward *et al.*, 1994), has been made in many variants, which were characterized by simplicity and a uniform peak acceleration ratio contained in a 3 dB band.

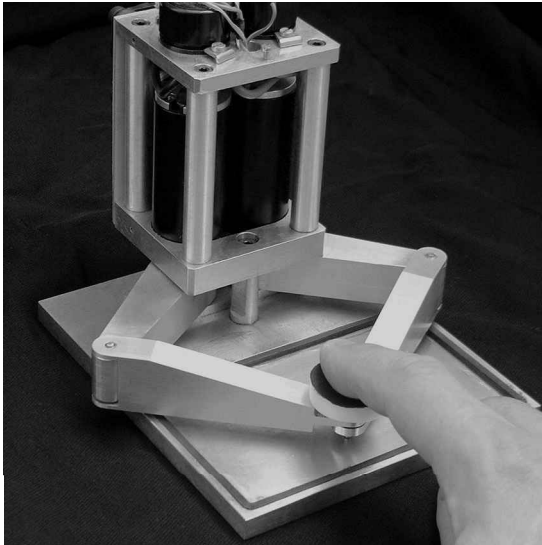
Figure 3 SensAble Technologies Inc. three degree of freedom Phantom™ 1.0, a common device for general research



Note: The Phantom features a clever torque amplification capstan drive where only one cable is shared by two motors and provides for static balancing.

It has two actuated degrees of freedom in the horizontal plane, provided by a stiff parallel linkage driven without transmission. The finger rests on the interface, resulting in a unilateral interaction (Figure 4). One variant is operated by the thumb and fits in the hand. Larger ones have a working area of 1.6 dm². An industrial version, the PenCat/Pro™, has a sensed 2.5 cm vertical movement, passively actuated by an elastic return.

Figure 4 From McGill University Haptics Laboratory, the planar workspace Pantograph allows for the simulated exploration of surfaces



Note: The interface neither needs to be grasped nor does it need to brace a finger. Simplicity yields high fidelity: the frequency response is flat to 400 Hz, it has three orders of magnitude of dynamic range, and resolves 10 μm displacements.
micron

5.11 A range of scales

Hannaford and co-workers have explored not only many influential design directions using direct-driven parallel linkages, but also torque amplification, and multiple finger isometric systems. One design is the “Pen-based” force display that uses actuator redundancy to increase the work-area footprint ratio (Buttolo and Hannaford, 1995). It showed how surprisingly effective and apparently small work-areas actually are.

5.12 Rotary controllers

A rotary knob with haptic feedback is also a device that is at the same time particularly simple and yet, rich in research questions and applications (MacLean *et al.* 1999). A haptic knob has been developed and commercialized by Immersion Corp. for vehicles (Figure 5).

5.13 Trackball

Keyson (1996) described a haptic device in the form of familiar trackball that was used to gain many insights into the effects of haptic feedback in GUI navigation. Two small DC motors drive the ball through a friction drive, providing

Figure 5 From Immersion Corp. a one degree of freedom device for navigation in user interfaces



Note: This device represents an exercise in minimalism, yet it achieves a crucial function in that it substitutes touch for vision when integrated in a vehicle.

two degrees of freedom of independent feedback.

5.14 Intermittent contact

An original device was described by Yoshikawa and Nagura (1997). It is both active and passive in the sense that the body interface is unilateral, yet intermittent. To achieve this, an annular end-effector is moved by a geared parallel linkage so as to approximate the surface patch of a represented object. Should the user move her or his finger to another surface patch, the finger would always encounter an approximating surface.

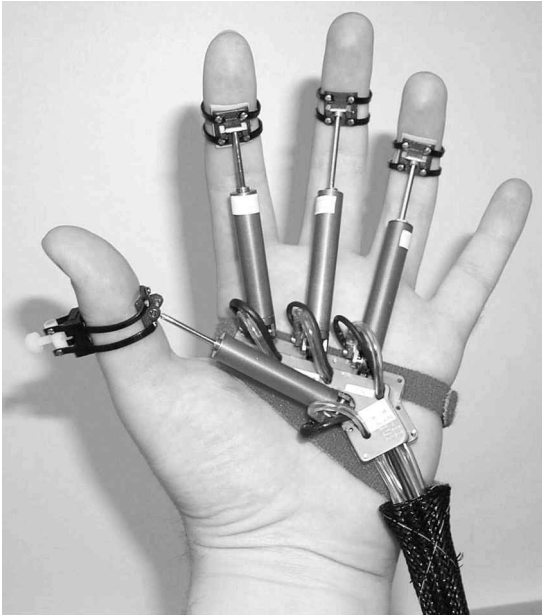
5.15 Consumer market

One particular aspect of haptic device design is cost. The main types of consumer market devices include gamepads with vibro-tactile feedback (rumble) and even true force feedback, tactile mice, force feedback trackballs, and force feedback joysticks (Rosenberg, 2001).

5.16 Virtual reality

Burdea and co-workers have pioneered a concept whereby pneumatic, force-producing elements act on discrete areas inside a user's hand. Portability makes the design adequate for use in conjunction with virtual reality gloves (Figure 6) (Burdea *et al.*, 1992. Performance modeling is described in Gomez *et al.* (1995).

Figure 6 From the Human-Machine Interface Laboratory of Rutgers University, the Master II-ND virtual reality force-feedback glove (new design)



Note: The use of pneumatic pistons makes it possible to achieve a low weight and hence a portable device to simulate the grasping of virtual objects.

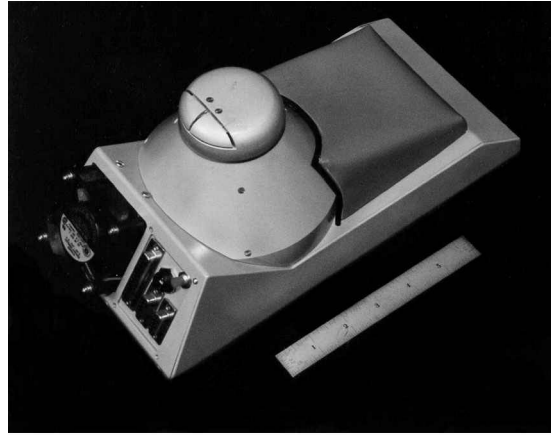
5.17 Arrays of vibro-tactors

Gunther *et al.* (2002) described a suit comprising a large collection of vibro-tactile transducers. This system is interesting in the sense that the motivation for its design has no particular utilitarian end: only the beauty and the harmony of the resulting sensations is sought. Recently Tan *et al.* (2003) described such an array embedded in a chair for purposes of vehicle operator directional cueing.

5.18 Magnetic levitation

Salcudean and co-workers have explored many high performance force-feedback designs featuring both direct driven parallel linkages and levitated Lorentz actuators. A prominent example is a miniature six degrees of freedom voice-coil levitated joystick that provides ultimate fidelity as it is very light and requires no moving part to be in contact with another, so that the system's noise floor is essentially determined by the driving and sensing electronics (Figure 7) (Salcudean and Parker, 1997). Larger scale similar designs exist (Berkelman *et al.*, 1999).

Figure 7 From the University of British Columbia Robotics and Control Laboratory, the six degree of freedom magnetically levitated joystick



Note: While this device has a comparatively small workspace, the total absence of contact between moving surfaces and a highly optimized structural design afford ultimate fidelity.

5.19 Hybrid kinematics

A six degree of freedom device, extensible to seven, is described in Hayward *et al.* (1998). It is characterized by a wide dynamic range and six-axis static and dynamic balancing. The primary user interface is a stylus, but could accommodate scissor-like loops. Its design is “wrist partitioned”, the position and orientation stages each being parallel mechanisms. The position stage is directly driven and the orientation stage is driven through remotizing tendons with a differential tensioning technique that operates with low tension and hence low friction. A commercial version six degree of freedom device is available from MPB Technologies Inc. (Figure 8).

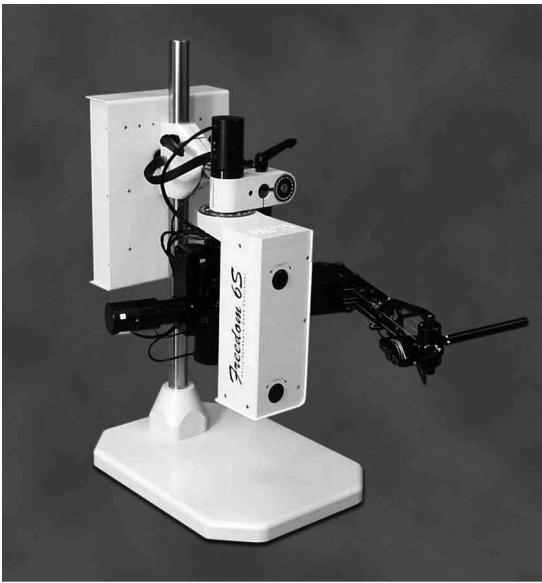
5.20 Isometric device

There are very few examples of isometric devices due to the design complexities resulting from the use of force sensors. Nevertheless, experimental devices were developed (MacLean and Durfee, 1995) and industrial systems exist (FCS Controls Systems, Figure 9).

6. Conclusion

This paper discussed about haptic interfaces and their applications. The function of several devices was described as part of a more general

Figure 8 From MPB Technologies Inc., the six degree of freedom Freedom-6S provides uncanny virtual presence because of a very crisp response in all three translations and three rotations



Note: The judicious specification of forces and torques makes it possible to precisely simulate interactions between tool and object taking place anywhere outside the physical extent of the handle: i.e. the tool is truly virtual.

Figure 9 The HapticMaster from FCS Control Systems, unlike most devices, is an isometric device



Note: It tracks a commanded displacement which is computed in response to a measured force applied by the user (admittance specification). It has three degrees of freedom, two of which are sliding joints.

problem of creating haptic interfaces. The function of these interfaces was portrayed as an attempt to tap human sensory-motor skills to improve communication between the humans and machines. Linking device performance to human performance is important and research is currently being carried out on this problem. However, the more systematic study of the connection between the devices and specific tasks and applications will probably be even more important.

References

- Adams, J.R., Clowden, D. and Hannaford, B. (2001), "Virtual training for a manual assembly task", *Haptics-e*, Vol. 2 No. 2, Available at Web site: <http://www.haptics-e.org>
- Adelstein, B.D. and Rosen, M.J. (1992), "Design and implementation of a force reflective manipulandum for manual control research", *Proc. DSC-Vol. 42, Advances in Robotics, ASME Winter Annual Meeting*, pp. 1-12.
- Akamatsu, M., Sato, S. and MacKenzie, I.S. (1994), "Multimodal mouse: a mouse-type device with tactile and force display", *Presence*, Vol. 3 No. 1, pp. 73-80.
- Basdogan, C. and Srinivasan, M.A. (2002), "Haptic rendering in virtual environments", in Stanney, K. (Ed.), *Handbook of Virtual Environments*, Lawrence Erlbaum, Inc., London.
- Bejczy, A.K. and Salisbury, J.K. (1980), "Kinesthetic coupling between operator and remote manipulator", *Proceedings International Computer Technology Conference, ASME, San Francisco*, pp. 197-211.
- Bergamasco, M. and Avizzano, C.A. (1997), "Virtual environment technologies in rehabilitation", *Proc. of IEEE-RSJ-SICE Ro-Man*.
- Bergamasco, M., Allota, B., Bisio, L., Ferretti, L., Parini, G., Prisco, G.M., Salsedo, F. and Sartini, G. (1992), "An arm exoskeleton system for teleoperation and virtual environments applications", *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 1449-54.
- Berkelman, P.J., Hollis, R.L. and Baraff, D. (1999), "Interaction with a realtime dynamic environment simulation using a magnetic levitation haptic interface device", *Proc. Int. IEEE International Conference on Robotics and Automation*, pp. 3261-6.
- Berthoz, A. (1996), *Le sens du mouvement*, Editions Odile Jacob, Paris.
- Biggs, S.J. and Srinivasan, M.A. (2002), "Haptic interfaces", in Stanney, K. (Ed.), *Handbook of Virtual Environments*, Lawrence Erlbaum, Inc., London.
- Brooks, F.P., Ouh-Young, M., Batter, J.J. and Kilpatrick, P.J. (1990), "Project GROPE: haptic displays for scientific visualization", *Computer Graphics: Proc. SIGGRAPH '90*, pp. 177-85.
- Brown, J.M. and Colgate, J.E. (1997), "Passive implementation of multi-body simulations for haptic display", *Proceedings International Mechanical Engineering Congress and Exhibition*, Vol.61, pp. 85-92.

- Burdea, G.C., Zhuang, J.A., Rosko, E., Silver, D. and Langrama, N. (1992), "A portable dextrous master with force feedback", *Presence: Teleoperators and Virtual Environments*, Vol. 1, pp. 18-28.
- Buttolo, P. and Hannaford, B. (1995), "Advantages of actuation redundancy for the design of haptic-displays", *Proceedings ASME Fourth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*.
- Cadoz, C. and Ramstein, C. (1990), "Capture, representation, and 'composition' of the instrumental gesture", *Proceedings International Computer Music Conference*, pp. 53-6.
- Cadoz, C., Lisowski, L. and Florenz, J.L. (1990), "Modular feedback keyboard", *Computer Music Journal*, Vol. 14 No. 2, pp. 47-50.
- Colgate, J.E. and Schenkel, G.G. (1997), "Passivity of a class of sampled-data systems: application to haptic interfaces", *Journal of Robotic Systems*, Vol. 14 No. 1, pp. 37-47.
- Craig, J.C. and Rollman, G.B. (1999), "Somesthesis", *Annual Review of Psychology*, Vol. 50, pp. 305-31.
- Darian-Smith, I. (1984), "The sense of touch: performance and peripheral neural processes", *Handbook of Physiology. The Nervous System Sensory Processes, Sect. 1, Vol. III, A. Physiology Soc.*, Bethesda, MD, pp. 739-88.
- Delp, S.L., Loan, J.P., Basdogan, C. and Rosen, J.M. (1997), "Surgical simulation: an emerging technology for emergency medical training", *Presence: Teleoperators and Virtual Environments*, Vol. 6, pp. 147-59.
- Dufresne, A., Martial, O. and Ramstein, C. (1995), "Multimodal user interface system for blind and 'visually occupied' users: ergonomic evaluation of the haptic and auditive dimensions", *Proc. Interact '95*.
- Ellis, R.E., Ismaeil, O.M. and Lipsett, M. (1993), "Design and evaluation of a high-performance prototype planar haptic interface", *Proceedings Advances in Robotics, Mechatronics, and Haptic Interfaces: ASME, DSC Vol. 9*, pp. 55-64.
- Falvo, M.R., Superfine, S., Washburn, M., Finch, R.M., Taylor, V.L., Chi and Brooks, F.P. Jr (1996), "The nanomanipulator: a teleoperator for manipulating materials at the nanometer scale", *Proceedings International Symposium on the Science and Technology of Atomically Engineered Materials*, World Scientific Publishing, Singapore, pp. 579-86.
- Flanagan, J.R. and Lederman, S.J. (2001), "Neurobiology: feeling bumps and holes", *Nature*, Vol. 412, pp. 389-91.
- Flateau, C.R., Greeb, F.J. and Booker, R.A. (1973), "Some preliminary correlations between control modes of manipulators systems and their performance indices", *Proceedings First National Conference, Remotely Manned Systems, Exploration and Operation in Space*, California Institute of Technology.
- Goertz, R.C. (1952), "Fundamentals of general purpose remote manipulators", *Nucleonics*, Vol. 10 No. 11, pp. 36-42.
- Goertz, R.C. (1964), "Manipulator systems development at ANL", *Proceedings of 12th Conference on Remote System Technology*.
- Gomez, D., Burdea, G. and Langrana, N. (1995), "Modeling of the rutgers master II haptic display", *Proceedings of Fourth Annual Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems, ASME*, pp. 727-34.
- Goodwin, A.W., Macefield, V.G. and Bisley, J.W. (1997), "Encoding of object curvature by tactile afferents from human fingers", *J. American Physiological Society*, Vol. 22, pp. 2881-8.
- Gunther, E.G., Davenport and O'Modhrain, S. (2002), "Cutaneous grooves: composing for the sense of touch", *Proc. 2002 International Conference on New Interfaces for Musical Expression NIME02*, pp. 37-42.
- Hannaford, B. and Ryu, J-H. (2002), "Time domain passivity control of haptic interfaces", *IEEE Transactions on Robotics and Automation*, Vol. 18, pp. 1-10.
- Hannaford, B. and Szakaly, Z. (1989), "Force feedback cursor control", *NASA Tech. Briefs*, Vol. 13 No. 11, Item 21.
- Hayward, V. and Astley, O.R. (1996), "Performance measures for haptic interfaces", in Giralto, G. and Hirzinger, G. (Eds), *Robotics Research: The 7th International Symposium*, Springer-Verlag, Berlin, pp. 195-207.
- Hayward, V., Choksi, J., Lanvin, G. and Ramstein, C. (1994), "Design and multi-objective optimization of a linkage for a haptic interface", in Lenarcic, J. and Ravan, B. (Eds), *Advances in Robot Kinematics*, Kluwer Academic, Dordrecht, pp. 352-9.
- Hayward, V., Gregorio, P., Astley, O.R., Greenish, S., Doyon, M., Lessard, L., McDougall, M., Sinclair, I., Boelen, S., Chen, X., Demers, J.P., Poulin, J., Benguigui, I., Almey, N., Makuc, B. and Zhang, X. (1998), "Freedom-7: a high fidelity seven axis haptic device with application to surgical training", in Casals, A. and de Almeida, A.T. (Eds), *Experimental Robotics V*, Vol. 232, Lecture Notes in Control and Information Science, pp. 445-56.
- Hogan, N., Kay, B.A., Fasse, E.D. and Mussa-Ivaldi, F.A. (1990), "Haptic illusions: experiments on human manipulation and perception of 'virtual objects'", *Cold Spring Harbor Symposia on Quantitative Biology*, Vol. 55, pp. 925-93.
- Howe, R.D. (1992), "A force reflecting teleoperated hand system for the study of tactile sensing in precision manipulation", *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1321-6.
- Iwata, H. (1990), "Artificial reality with force feedback: development of desktop virtual space with a compact master manipulator", *Computer Graphics*, Vol. 24 No. 4, pp. 165-70.
- Johnson, K.O. (2001), "The roles and functions of cutaneous mechanoreceptors", *Curr. Opin. Neurobiol.*, Vol. 11, pp. 455-61.
- Johnson, K.O. and Hsiao, S.S. (1992), "Neural mechanisms of tactual form and texture perception", *Annu. Rev. Neurosci.*, Vol. 15, pp. 227-50.
- Kelley, A.J. and Salcudean, S.E. (1994), "On the development of a force-feedback mouse and its integration into a graphical user interface", *Proceedings ASME Dynamic Systems and Control Division, DSC*, Vol. 55-1, pp. 287-8.

- Keyson, D.V. (1996), "Touch in user in interface navigation", PhD thesis, Technische Universiteit Eindhoven, Netherlands.
- Krebs, H.I., Hogan, N., Aisen, M.L. and Volpe, B.T. (1998), "Robot-aided neurorehabilitation", *IEEE Transactions on Rehabilitation Engineering*, Vol. 6 No. 1, pp. 75-86.
- LaMotte, R.H. and Srinivasan, M.A. (1991), "Surface microgeometry: neural encoding and perception", in Franzen, A.W. and Westman, J. (Eds), *Information Processing in the Somatosensory System*, Macmillan, London, pp. 49-58.
- Luecke, G.R., Chai, Y.H., Winkler, J.A. and Edwards, J.C. (1996), "An exoskeleton manipulator for application of electromagnetic virtual forces", *Proceedings ASME Dynamic Systems and Control Division*, DSC Vol. 58, pp. 489-94.
- MacLean, K.E. (1996), "The 'haptic' camera: a technique for characterizing and playing back haptic properties of real environments", *Proceedings ASME Dynamic Systems and Control Division DSC*, 58, pp. 459-67.
- MacLean, K.E. and Durfee, W.K. (1995), "An apparatus to study the emulation of haptic feedback", *Proceedings of the ASME Dynamic Systems and Control Division*, Vol. 57 No. 2, pp. 615-21.
- MacLean, K.E., Roderick and Jayne, B. (1999), "Smart tangible displays in the everyday world: a haptic door knob", *Proc. IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics (AIM'99)*.
- Mahvash, M. and Hayward, V. (2003), "Passivity-based high-fidelity based haptic rendering of contact", *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 3722-8.
- Massie, T.H. and Salisbury, J.K. (1994), "The phantom interface: a device for probing virtual objects", *Proc. ASME Winter Annual Meeting, Symposium on Haptic Interfaces for a virtual environment and teleoperator systems*.
- McNeely, W., Puterbaugh, K. and Troy, J. (1999), "Six degree-of-freedom haptic rendering using voxel sampling", *Proc. of ACM SIGGRAPH*, pp. 401-8.
- Miller, B., Colgate, J.E. and Freeman, R.A. (1999), "Guaranteed stability of haptic systems with nonlinear virtual environments", *IEEE T. on Robot. Automat.*
- Millman, P.A., Stanley, M. and Colgate, J.E. (1993), "Design of a high-performance haptic interface to virtual environments", *Proceedings IEEE Virtual Reality Annual International Symposium VRAIS'93*, pp. 216-21.
- Minsky, M. (1995), "Computational haptics: the sandpaper system for synthesizing texture for a force-feedback display", PhD dissertation, Massachusetts Institute of Technology.
- Morgenbesser, H.B. and Srinivasan, M.A. (1996), "Force shading for haptic shape perception", *Proc. Fifth Annual Symp. on Haptic Interfaces for Virtual Envir. and Teleop. Syst., ASME Dyn. Syst. and Cont. Div.*, DSC Vol. 58, pp. 407-12.
- Nahvi, A., Nelson, D., Hollerbach, J.M. and Johnson, D.E. (1998), "Haptic manipulation of virtual mechanisms from mechanical CAD designs", *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 375-80.
- Okamura, A.M., Hage, M.W., Cutosky, M.R. and Dennerlein, J.T. (2000), "Improving reality-based models for vibration feedback", *Proceedings Haptic Interfaces for Virtual Environment and Teleoperator Systems Symposium, ASME, IMECE-2000*, Vol. 69 No. 2, pp. 1117-24.
- O'Modhrain, M.S. (2000), "Playing by feel: incorporating haptic feedback into computer-based musical instruments", PhD dissertation, Stanford University.
- Payette, J., Hayward, V., Ramstein, C. and Bergeron, D. (1996), "Evaluation of a force-feedback (haptic) computer pointing device in zero gravity", *Proceedings Fifth Annual Symposium on Haptic Interfaces for Virtual Environments and Teleoperated Systems, ASME, DSC*, Vol. 58, pp. 547-53.
- Ramstein, C. and Hayward, V. (1994), "The pantograph: a large workspace haptic device for a multi-modal human-computer interaction", *Proceedings ACM/SIGCHI 1994 Conference on human factors in computing systems*.
- Robles-De-La-Torre, G. and Hayward, V. (2000), "Virtual surfaces and haptic shape perception", *Proceedings of the Haptic Interfaces for Virtual Environment and Teleoperator Systems Symposium, ASME IMECE 2000*, Orlando, Florida, USA. *Proc. ASME*, Vol. 69 No. 2, pp. 1081-7.
- Robles-De-La-Torre, G. and Hayward, V. (2001), "Force can overcome object geometry in the perception of shape through active touch", *Nature*, Vol. 412, pp. 445-8.
- Rosenberg, L. (2001), "State of the haptics industry", Unpublished talk given at the *Institute of Mathematics and its Applications Workshop, Haptics, Virtual Reality, and Human Computer Interaction*, 14-15 June 2001, University of Minnesota. Available at: <http://silver.ima.umn.edu/talks/workshops/6-14-15.2001/index.html>
- Rovan, B. and Hayward, V. (2000), "Typology of tactile sounds and their synthesis in gesture driven computer music performance", in Wanderley, M. and Battier, M. (Eds), *Trends in Gestural Control of Music*, IRCAM, Paris, pp. 297-320.
- Salcudean, S.E. and Parker, N.R. (1997), "6-DOF desk-top voice-coil joystick", *Proceedings 6th Annual Symposium on Haptic Interfaces for Virtual Environments and Teleoperation Systems, ASME Winter Annual Meeting, DSC*, Vol. 61, pp. 131-8.
- Salisbury, K., Brock, D., Massie, T., Swarup, N. and Zilles, C. (1995), "Haptic rendering: programming touch interaction with virtual objects", *Proc. Sym. on Interactive 3D Graphics, ACM*, pp. 123-30.
- Sherrick, C.E. (1985), "Touch as a communicative sense", *J. Acoust. Soc. Am.*, Vol. 77 No. 1, pp. 218-19.
- Tan, H.Z., Gray, R., Young, J.J. and Traylor, R. (2003), "A haptic back display for attentional and directional cueing", *Haptics-e*, Vol. 3 No. 1.
- Vertut, J., Marchal, P., Debrie, G., Petit, M., Francois, D. and Coiffet, P. (1976), "The MA-23 bilateral servomanipulator system", *Proc. 24th Conf. on Remote Systems Tech.*
- Weisenberger, J.M., Krier, M.J. and Rinker, M.A. (2000), "Judging the orientation of sinusoidal and square wave virtual gratings presented via 2-DOF and 3-DOF haptic interfaces", *Haptics-e*, Vol. 1 No. 4.
- Yoshikawa, T. and Nagura, A. (1997), "A touch and force display system for haptic interface", *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 3018-24.