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Haptic Interfaces and Devices

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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.

Keywords: Person-machine Communication, Haptic Interfaces, Haptic Interface Applications, Haptic Devices.

1 Introduction

Before the widespread use of computers in the workplace, 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 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 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 ten years ago, there were 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 (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 Sherrick (Sherrick, 1985; Craig and Rollman, 1999):

> "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 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 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 bi-directional 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 uni-directional 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 uni-directional 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.

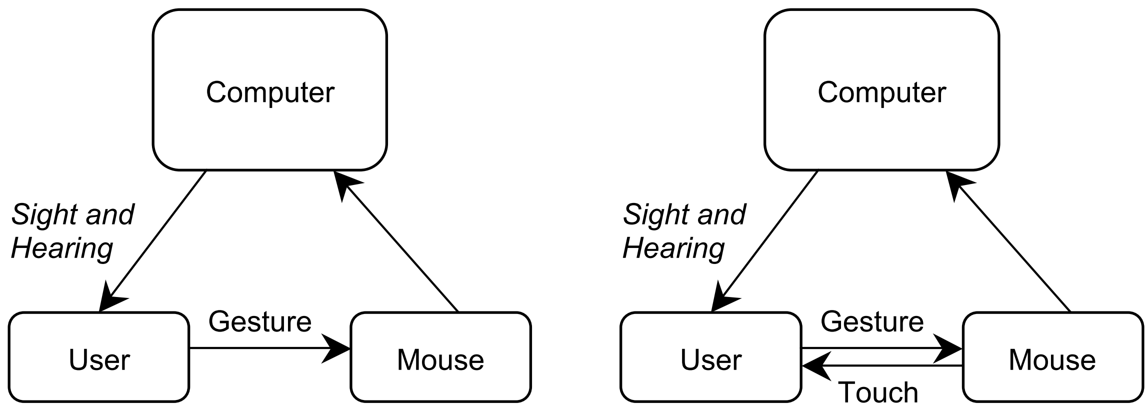

Figure 1. A distinguishing feature of haptic interfaces is the simultaneous exchange of information between the user and the machine.

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 kinaesthetic 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 two categories. They are inert or 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 nonholonomic 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 case 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 (Mahvash & Hayward, 2003, Hannaford & Ryu, 2002, Brown & Colgate, 1997, Miller et al., 1999, Colgate and Shenkel, 1997, 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 of 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, bi-directionality 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" to and 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" (see 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 re-create 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. (see 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 (Goertz, 1952; Goertz, 1964; Flateau et al., 1973; Vertut et al., 1976; Bejczy and Salisbury, 1980). 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 (GUI's) 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 in computer graphics is called the "quest for realism". 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 commercial activities, a 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 & Szakaly, 1989; Kelley & Salcudean, 1994; Ramstein & Hayward,1994). Today, 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.

Force-reflecting input devices for use with graphical user interfaces. As just 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.

Games. Modes of interaction and the sense of user immersion are greatly enhanced by applying force feedback to the player. Dexterity games previously available 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.

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), auditively (spatialization), and also haptically. This raises the question of authoring tools (such as Immersion Studio[tm]) and their necessity for the design of haptic sensations. Material properties can also be conveyed. A frequently mentioned case is that of online catalogues. A larger set of possibilities will almost certainly require the development of practical, distributed tactile displays, which are not yet available.

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: multidimensional 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 tunnelling and atomic force microscopes (Falvo et al., 1996).

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 existing MIDI fixed interfaces (Rovan & Hayward, 2000). In the graphic arts and design, especially the creation of animation, much activity is under way (O'Modhrain, 2000).

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).

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^{tm} equiped 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).

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).

Manufacturing. In manufacturing, many opportunities exist. For example, haptics can assist design for assembly, in terms of reducing the need for prototyping, 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.

Telerobotics and teleoperation. As commented previously, 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.

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.

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

Scientific Study of Touch. Last but not least, the availability of haptic devices makes it possible to study the haptic channel in humans (and other species) in exciting and perhaps previously impossible ways. Haptic devices allow the creation of special, computer-controlled stimuli which are used in studies that explore how 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; Weisenberg et al., 2000; Robles-De-La-Torre & Hayward, 2000; Robles-De-La-Torre & Hayward, 2001). In turn, the knowledge gained of the haptic function contributes to the development of new haptic interfaces and applications (Berthoz, 1997, Flanagan & Lederman, 2001; Biggs and Srinivasan, 2002; Basdogan and Srinivasan, 2002).

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, vibro-tactile 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 and Hsiao, 1992; LaMotte Srinivasan, 1991; Johnson, 2001).

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 two square meters; it weighs about five kilograms, its innervation is up to hundreds of receptors per cm^2). 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 & 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 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 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 bi-directional 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 actual physical objects (Minsky, 1995; Morgenbesser & Srinivasan, 1996; Robles-De-La-Torre & Hayward, 2001; Flanagan & Lederman, 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 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 & Astley (1996). In keeping with the focus of this section, the description of entire families of haptic devices, completely passive devices, foot contacting devices, distributed tactile displays, unfortunately had to be omitted, despite significant activity in all these areas.

Programmable Keyboard. One of the most documented examples of a multiple force-feedback implementation is the Clavier Rétroactif Modulaire, a project headed by Cadoz, that consists of a piano-like Lorentz-actuated keyboard providing computer-driven force feedback for each of its sixteen keys (Cadoz et al., 1990), and directed at musical creation research (Cadoz & Ramstein 1990).

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).

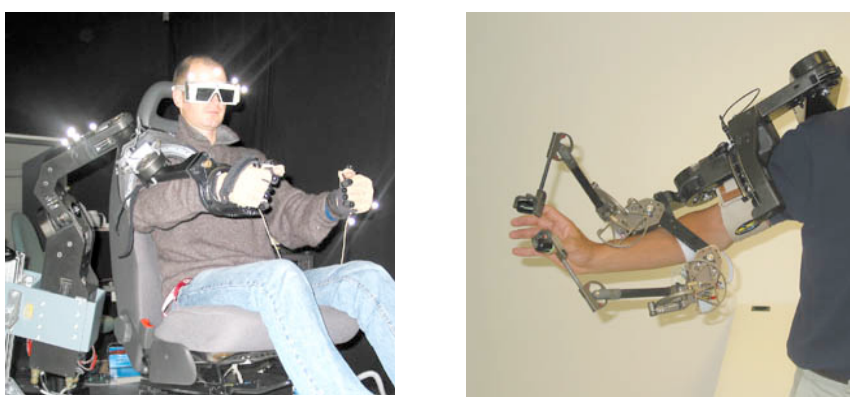

Figure 2. The PERCRO Laboratory (Scuola Superiore di studi Universitari S. Anna, Pisa, Italy) has extensive experience with the development of exoskeleton-type haptic interfaces. The left panel shows such a device applied to the simulation of the driving experience for cockpit design optimization. The right panel shows a variant of this device accommodating two additional sub-devices able to simulate the manipulation of objects “out of thin air”.

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 in (Iwata, 1990); several versions have been developed thereafter.

Grasping. Howe 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 (Howe, 1992). The user's fingers interact unilaterally with the device on the inner side of boxes, allowing precision grip.

Point Interaction. The Phantom^{tm} 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 (see Figure 3). There are three actuated degrees of freedom and three sensed orientations. A typical configuration has a work volume of 2.7 cubic decimetres. 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 & Salisbury, 1994) and is commercially available.

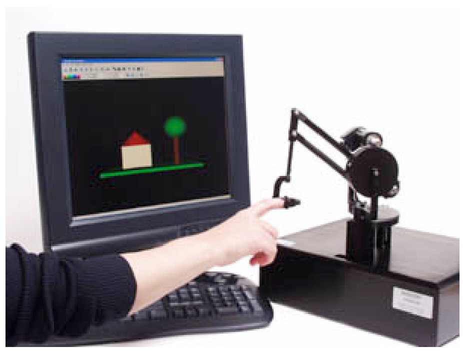

Figure 3. SensAble Technologies Inc. three degree-of-freedom Phantom^{tm} 1.0, a common device for general research. The Phantom features a clever torque amplification capstan drive where only one cable is shared by two motors and provides for static balancing.

High Power Devices. Colgate and his group have created a 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).

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

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

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

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. 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 (see Figure 4). One variant is operated by the thumb and fits in the hand. Larger ones have a working area of 1.6 square decimetres. An industrial version, the PenCat/Pro$^{\text{tm}}$, has a sensed 2.5 cm vertical movement, passively actuated by an elastic return.

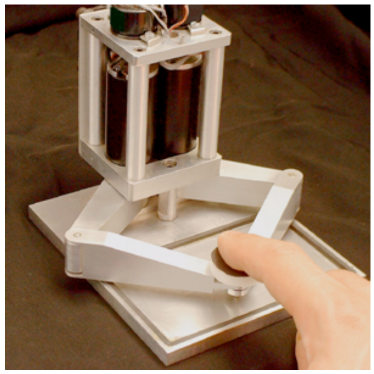

Figure 4. From McGill University Haptics Laboratory, the planar workspace Pantograph allows for the simulated exploration of surfaces. The interface neither needs to be grasped nor does it need to brace a finger. Simplicity yields high fidelity: the frequency response is flat to 400 Hz, it has three orders of magnitude of dynamic range, and resolves 10 μm displacements.

A Range of Scales. Hannaford and co-workers have explored 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 & Hannaford, 1995). It showed how surprisingly effective apparently small work-areas actually are.

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 (See Figure 5).

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

Trackball. Keyson (1996) describes a haptic device in the form of familiar trackball that was used to gain many insights into the effects of haptic feedback in graphical user interface navigation. Two small DC motors drive the ball through a friction drive, providing two degrees of freedom of independent feedback.

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.

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).

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 (Burdea et al., 1992, see Figure 6). 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). The use of pneumatic pistons makes to possible to achieve a low weight and hence a portable device to simulate the grasping of virtual objects.

Arrays of vibro-tactors. Gunther et al. (2002) describe 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) describe such an array embedded in a chair for purposes of vehicle operator directional cueing.

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 (Salcudean & Parker, 1997, see Figure 7). Larger scale similar designs exist (Berkelman et al., 1999).

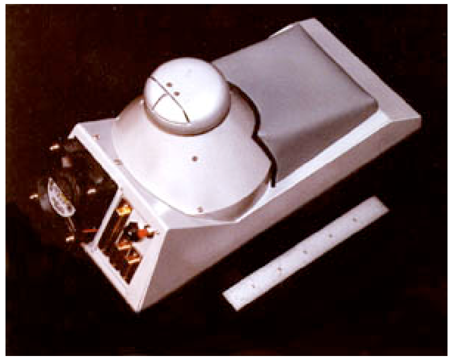

Figure 7. From the University of British Columbia Robotics and Control Laboratory, the six degree-of-freedom magnetically levitated joystick. While this device has a comparatively small workspace, the total absence of contact between moving surfaces and a highly optimized structural design afford ultimate fidelity.

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 direct 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 6 degree-of-freedom device is available from MPB Technologies Inc. (see Figure 8).

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. 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.

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, see Figure 9).

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

6 Conclusion

This article discussed haptic interfaces and their applications. The function of several devices was described as part of a more general 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 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 devices and specific tasks and applications will probably be even more important.

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