Haptics: An Introduction

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***Abstract*—As haptic interfaces become more prevalent in the computing world, it is necessary to understand how the somatosensory system could be used in designing novel haptic interfaces. This paper provides a brief summary of the somatosensory system,: its function, sensory receptors and how it processes different stimuli. We also provide a summary of current haptic interfaces, and some of the limitations inherent in these interfaces.**

***Index Terms*—Haptics, Somatosensory System**

I. Introduction

Haptic interfaces, interfaces that allow the user to physically interact with virtual objects, are novel interfaces that could facilitate our interaction with immersive virtual environments. Haptic interfaces utilize our somatic senses, also called somatosensory systems, to transfer the information from a virtual environment into a corresponding physical stimulus [2, 17, and 15]. This stimulus is usually manifested as either tactile feedback, the sensation of a virtual object applied to the skin; or force feedback, the sensation of weight or resistance in a virtual world felt by the end user [17]. While these interfaces provide adequate means of simulating physical interactions with virtual environments, they do not take into consideration how the somatosensory system processes information. As such, it is important to comprehend how the somatosensory system incorporates the information and manifests the corresponding haptic sensory feedback.

In this paper, we seek to provide an overview of how the somatosensory system works, how it processes information, and what kind of sensory apparatus are available within the human body that process haptic information. Furthermore, we will provide a review of some of the more prevalent haptic interface technologies available and in current development, as well as detail of the limitations present in these systems.

II. Somatosensory System

A. Overview

The somatosensory system is composed numerous sensory modalities spread throughout the body. Among these include: the skin sensation of touch, temperature, pain, as well as propioception, the sense that tells the brain what is occurring beneath the body surface [2, 19]. The modalities differ in their receptors, pathways, and end targets in the brain and in their level of crossing communication with the adjacent side of the brain. This is necessary, as any signal that traverses the cerebral cortex "will have to cross over at some point, because the cerebral cortex operates on a contralateral (opposite side) basis" [19]. The touch system crosses high in the medulla, whereas the pain system crosses low in the spinal cord. Curiously, the propioceptive system doesn't cross, as it inputs directly into the cerebellum, not crossing in any form [19].

The touch system, the sensory system directly used by haptic interfaces, directly handles all signals emitted from the neck down, as facial sensation is directly handled by cranial nerves. We now proceed to describe in some detail the nervous pathways handled by the touch system. A visual model of the touch system is represented in Figure 1.

Once a signal enters the touch nervous system through sensory axons, they are routed to the dorsal root ganglion: a cluster of sensory neurons located outside the spinal cord [19]. These sensory neurons are unique in that the signal does not pass through the cell body. "Instead, the cell body sits off to one side, without dendrites, and the signal passes directly from the distal axon process to the proximal process" [19]. The proximal end of the axon enters the dorsal half of the spinal cord, and immediately turns up the cord towards the brain. These axons are called the **primary afferents** (pink), because they are the same axons that brought the signal into the cord [19]. In general, *afferent* means towards the brain, and *efferent* means away from it. The axons ascend in the dorsal white matter of the spinal cord.

At the medulla, the primary afferents finally synapse. The neurons receiving the synapse are now called the **secondary afferents** (purple). The secondary afferents cross immediately, and form a new tract on the other side of the brainstem. This tract of secondary afferents will ascend all the way to the **thalamus**, which is the clearinghouse for everything that wants to get into cortex. Once in thalamus, they will synapse, and a third and final neuron (lavender) will go to **cerebral cortex**, the final target [19].

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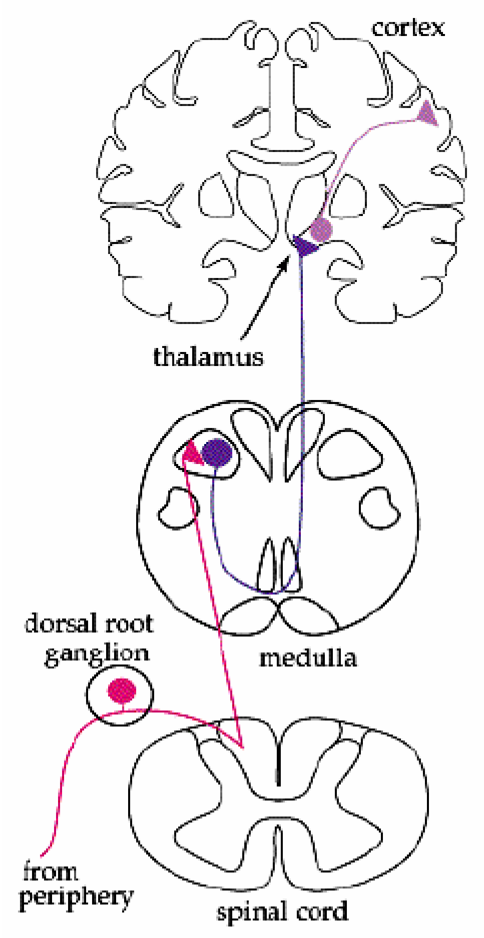

Figure 1: Touch System

B. Tactile Sensing

"The most active role in tactile exploration is played by hairless skin … covering the palmar and fingertip regions of the body", as they have a very high sensorial density of specialized receptors that correspond to a large sensory cortex surface [17]. Hairless, or glabulous skin, has five major types or receptors: free receptors, Meissner corpuscles, Merkel's disks, Pacinian corpuscles and Ruffini corpuscles. Hairy skin, on the other hand, has an additional receptor, the hair-root follicle, which transducer the deformation of skin into neural activity [2, 17].

The free nerve endings are located close to the surface of both hairy and glabulous skin, and respond to distributed pain [17]. Meissner corpuscles are present in over 40 percent of the hand tactile receptors, and are designed to best detect movement across the skin; they serve as great velocity detectors. Merkel's disks, on the other hand, are designed to best detect edges and pressure stimulus, and can also provide vibration information. Pacinian corpuscles are the largest receptors, and are suited for acceleration detection. Finally, Ruffini corpuscles are designed to detect pressure and skin shear, as well as any changes in temperature [17].

Tactile receptors are different from most receptors present in the human body in that they react to a change from the status quo. After a period of time, even if the stimulus is present, some tactile receptors will ignore the stimulus [2]. However, some tactile receptors are designed to rapidly adapt to stimulus, whereas others take a longer time to adapt. Merkel disks and Ruffini corpuscles react slowly to any stimulus, providing a regular discharge rate for a steady load [17]. However, Meissner corpuscles discharge rather quickly, usually "at the onset of stimulus", making them best suitable to detect velocity [17]. Pacinian corpuscles have been found to be sensitive to vibrations near 200 Hz, making them perfect for detecting acceleration and vibration.

Furthermore, each tactile receptor varies in their spatial resolution which is inversely proportional to their receptive fields. Meissner corpuscles and Merkel disks have a very accurate spatial resolution, due to their small receptive field, whereas Pacinian and Ruffini corpuscles have low spatial resolution. Overall, this translates to a spatial resolution that can vary from 1-2 mm^2 up to $45cm^2$, with the fingertips possessing the highest spatial resolution, close to $1mm^2$ [17].

Different experiments have shown that there are a particular range of frequencies where the tactile system can perceive different sources of stimuli fluctuating at said frequencies [17]. These experiments have shown that: at around 5 – 10 kHz, the human finger is able to sense vibrational changes while performing skillful manipulative tasks. However, after 320 Hz, the human finger cannot discriminate between two consecutive force input signals. 20 – 30 Hz is the minimum bandwidth necessary to discern the presence of different force inputs signals. After 12 -16 Hz, human fingers cannot correct their grasping forces if the grasped object slips. Also, after 8 - 12 Hz, human fingers cannot correct for its positional disturbances, and after 5 – 10 Hz, they are also incapable of comfortably applying force and motion commands. Finally, after 2 Hz, the human finger cannot react to an unexpected force/position signal [17].

C. Somatosensory Signal Processing

It is interesting to note how the somatosensory system encodes information in regards to pain, changes in temperature and changes in tactile perception. For instance, when nocioceptors, the receptors that handle information in regards to pain, are subjected to constant pressure caused by a square-wave like indentation, the nocioceptors fire a sequence of neural action potentials as soon as this new stimuli is perceived. However, the nocioceptors ignore the stimuli soon afterwards [15]. Yet, when we compare the same nocioceptors against two square-wave indentations of 80um and 150um, these nocioceptors emit neural action potential as soon as the new stimulus is present, but surprisingly, they continue to emit action potentials even after one expects the nocioceptors to have adjusted to the input stimulus [15]. Another experiment showed that as we increased the temperature in a step-wise manner, our nocioceptors and thermoceptors encode the information and transmit the changes in termperature to the brain as soon as they occur, up until a certain temperature (in these experiments, 47 Celsius) is reached. At this temperature, the nocioceptors began firing continuously [15]. These findings suggest that the somatosensory system encoded information based on the frequency a neural action potential is received, and that the somatosensory system has a series of safeguards that, by overwhelming a person with pain, are designed to prevent further damage to take place.

In pursuing how the somatosensory system reacts to different input stimuli, [1] has conducted research into how the somatosensory system is affected by electrical stimulation. Based on their research findings, [1] showed that there is a convergence between mechanical and electrical stimulus. For example, when subjects were subjected to vibrotactile and electrical stimulus of the same frequency and in-phase, the mechanical vibration had a lower detection threshold [1]. Yet, when both signals were out of phase, there wasn't much difference in the detection threshold of both signals [1]. At the same time, [1] found that if the electrical and mechanical stimuli are present at the same sensation magnitude, the sensation area of the mechanical stimulus is larger. However, at differing magnitudes, the electrical stimulus could almost fully cancel out the mechanical sensation [1].

III. HAPTIC INTERFACES

We now proceed to describe some of the more prevalent haptic interfaces currently available.

A. SensAble Phantom

The SensAble Phantom line of haptic products are some of the more commercially available haptic interfaces. They are designed to provide haptic feedback through the use of a mechanical arm which is able to resist and exert forces up to 8 Newtons [18]. All of the SensAble Phantom models are designed to be portable (in the sense that they are not physically attached to any surface). Users interact with the virtual environment through the use of a stylus attached to the mechanical arm. This allows users to have six-degrees-of-freedom when interfacing with a virtual environment, as well as freedom of wrist movement.

One of the main limitations of the SensAble Phantom, indeed of all currently available haptic interfaces, is that they require a duplicate version of the graphical environment, embedded with the relevant physical and haptic feedback information that will allow the haptic device to react accordingly to the virtual environment. The programmer then has to ensure that the haptic and visual models are in constant sync, thereby adding a layer of complexity to a virtual environment, thus limiting either its visual realism, tactic perception, or both. While there are in development programs and databases that aim to predict haptic movements, correlate visual and haptic information on a single database and understand how interconnected are the vision and tactile systems [5, 3, 8, 4 , 11, 16], these areas of research are not mature enough where they could be fully implemented.

The main problem associated with the SensAble Phantom is that by giving the user only a stylus as a means of inputting and outputting haptic information, one disjoints hand-eye coordination. This disjunction results in a less-intuitive understanding of one's virtual environment, thereby making users train themselves to interact with a virtual environment in a manner that is appropriate to the system, as opposed to the system being as intuitive as possible in order to minimize the amount of training of novice users.

Furthermore, the SensAble device is a fragile system. Due to its mechanical nature, it is subject to wear and tear which causes it to break down frequently. Also, due to its limited mobility, the Phantom cannot be used in a large-scale virtual environment to provide haptic feedback.

B. CMU Magnetic Levitation Haptic Device

Carnegie-Mellon University has designed a novel haptic interface based off of the Lorenz force magnetic levitation [14]. The interface works by allowing the user to grasp a levitated tool that is used to interact with virtual environment. This interface is capable of rendering "the motion, shape, resistance, and surface texture of simulated objects" [14]. The benefits of having a magnetic levitation haptic device is that it has high control bandwidths, allows for six degrees-of-freedom with one moving part, is not easily susceptible to wear and tear damages, and it has great position resolution and sensitivity within the confines of the magnetic field [14].

However, this interface is also limited in its operating range, as the user can only work within a narrow magnetic field. Furthermore, it still creates a disjunction between hand-eye coordination, thus requiring further training by users. This interface can only be used as an exploratory tool within a virtual environment, in that one can only react to what's already present in the virtual environment and as such is very difficult to create a new object with said interface.

C. Haptic Remote and Nintendo Wii

Palpable Machines Research Group in Dublin, Ireland, has incorporated a haptic interface into a common household device: the remote control. They've designed a series of children shows that enable children to interact with the program based on haptic cues embedded in the program. Haptic feedback is achieved through the use of a two degree-of-freedom force feedback gaming joystick [9].

While the interface itself is not as novel as some of the other haptic interfaces already discussed, it does highlight certain novel uses for haptic interfaces. A key characteristic of the Haptic Remote is that it allows for an unlimited range of motions, so long as there is communication between the television program and the remote.

This type of haptic feedback system is similar to the Nintendo's Wii haptic feedback system. Through the use of accelerometers, the Nintendo Wii controller is able to generate vibrational feedback to the user. While the feedback is not "realistic" in any sense of the word, the popularity of the Wii clearly shows that there is a demand for greater, unrestrained interaction between a user and a virtual environment.

D. HIRO-II

The HIRO II is an "anthropomorphic interface of the human arm from shoulder to fingertips" [13]. The interface can be divided into two parts: the arm, which is designed to mimic a human arm, has a total off 6 degrees of freedom; and the hand, with 5 fingers, each designed with 3 joints to allow for 3 degrees of freedom. The HIRO-II is an excellent interface for applications which require dexterous movements, such as, manipulations of deformable objects, grasping objects, etc. However, its main limitations lie in that it is a very complicated system to utilize at first [13], requiring extensive training of users. Also, it is a fixed device that is very difficult to travel with.

E. Surface Drawing

Caltech designed a system for creating "organic 3D shapes" in an intuitive manner [6]. Through the use of specially designed tools and a stereoscopic display, artists are able to generate freeform 3D structures with minimal training in regards to the user interface. Also, the user is able to draw in free space without the use of any tools other than their hands, so long as those gestures correspond to a predetermined set of commands.

Unfortunately, the Surface Drawing interface does not provide any sort of feedback to the end user [6]. Instead, the user relies on visual feedback in order to determine and fine-tune the characteristics of their virtual creations. Based on the advantages present in incorporating haptic interfaces, we can reasonably guess that by providing a haptic feedback to the Surface Drawing interface, we will be able to further facilitate the task of interacting with a virtual object, as a new set of information about the object's texture, dexterity, etc. are available to the artist. Furthermore, this technology could be further expanded to be utilized in areas where interaction with simulations and other virtual objects can be crucial, such as: surgical simulations, aircraft manufacturing, astronomical simulations, etc.

CONCLUSION

In conclusion, we have provided here a brief summary of the somatosensory system, how it acquires and processes information. Further, we have summarized in this paper some of the more prevalent and available haptic interfaces. By further analyzing the human somatosensory system, we believe that we will be able to identify key features and characteristics of said system that would be suitable for designing a new generation of haptic interfaces.

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