HAPTICS DEVICES FOR MEDICAL ROBOTS: MODEL AND CONTROL

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Abstract. *Haptics devices got a special role in many applications in different fields of knowledge, as in engineering, virtual reality applications and medicine, having a special spot in medical robots. The use of haptics devices looks to give back to the surgeon the capacity of perception from the surgical site (mainly touching), lost with the actual minimal invasive instruments, like laparoscopes. Its concepts involve concepts of neurosciences (somatosensory system) and mechatronics engineering, which are presented in this work. Our focus is in its application in medical robots, its constraints and needs. Haptics devices can be also used to training surgeons creating virtual procedures. This review paper presents a model of biological system based in the last studies in neurosciences; and a control model for this kind of device, comparing this mechanism with the literature.*

Keywords*. Haptics Systems, Somatosensory System, Minimally Invasive Surgery, Medical Robots, Force-feedback, Control.*

1. Introduction

Medicine and Engineering are each day more connected in diverses fields. Applications in single treatments up to intensive treatments can be found for this cooperative work. In special, surgery had a special approach from many researchers. The development of instruments made minimally invasive surgeries possible, allowing a treatment less injurious to the patient and a fast recovery, besides the economic aspects (e.g. hospital time and insurances). The robots got a special role in the surgery room in the past century, assisting the surgeon in different procedures and even carrying out it. These robotic systems are teleoperated by a surgeon in a console located in the surgery room or by distance. The traditional minimally invasive procedures, as the laparoscopic surgeries, have inspired the development of medical robots. One of the main issues for these projects is the loss of sensations from the surgical field in traditional minimally invasive surgery when compared with open surgery. In the laparoscopic surgery for example, the instruments are long shafts introduced into the patient by small incisions. This reduces the degrees of freedom of the professional, imposes other forces in the system (e.g. friction) and other constraints that requires from the surgeon an extensive training to have a better conscience of his actions and its consequences. Force sensing at the tip of a surgical tool is an important feature for more efficient and safer performance of tasks such as: cutting, testing, moving, and suturing tissues. Due to the length of laparoscopic tools, and the presence of friction and backlash in its linkages, forces are transmitted very poorly to the hand (Faraz et al., 2000). In addition, the lever effect of the tool around the incision point changes the magnitude and the direction of these forces. Also the tactile sensing is important for sensing the surface texture, and detecting small movements such as pulses in an artery. In laparoscopic tools all the information is lost and only the grasping force of the tool is sensed to some extent by the surgeon. Of course even in this case, its magnitude and stiffness is altered by all the intermediate mechanical linkages. In order to overcome these issues robotic systems have in its conception special mechanisms and control, haptic devices. Before describing these devices, it's important to understand the meaning of this concept and its origins.

1.1. Haptics: Origins

The term *haptics* has its etymology from the Greek word haptesthai (*apte??*) that means "to touch or to grasp". The word was first used as a scientific term in German (*haptik*) by the researcher Dessoir in 1892 meaning "the study of touch and tactile sensations, especially as a means of communication" (Sheridan, 1997). He made two subdivisions in his study: (a) contact sense, and (b) pselaphesia (active and passive touch) (Green, 2002). His study wasn't involved with Engineering but with Physiology and Psychology. However the pioneer in the study of touch is Ernst Heinrich Weber, professor of Anatomy and Physiology at Leipzig University. He divided touch into component sensations of weight, location and temperature, and relegated other sense qualities of the skin to the "general sensation".

The haptics involve multiple sensory and motor organs of body, such as the cutaneous sensors; and sensors in the muscles and joints. The psychologist J. J. Gibson, in 1966, described the haptic sense as the sensory-motor system

(Millman, 1995). In Medicine, the term haptics is not usually employed, though its study is often referred to as sensory systems or more generally somatosensory system.

2. Human Haptics Model

As described before the human haptics model is the subject of study in divers fields of science. The understanding of this model helps in the development of haptics devices. The study of this field got a special interest between the researches involved with blind people and others handicapped (Lima, 2001; Millman, 1995). The use of other senses to surmount the disability is developed to rehabilitate the person to a normal life. The development of neurosciences in the last centuries helped us to have a better understanding how this works (Bear et al., 2001). General senses in human beings could be elicited by stimulating appropriate receptors that were widespread throughout the body. General senses were designated *somatic* if the receptors were located in the body wall or periphery and visceral if the receptors were located within the organs of the body cavities (Rhoades et al., 2003). Visceral and somatic senses include pain, temperature change (warm and cold), touch and pressure, and proprioception (muscle, tendon, and joint capsule stretch). The receptors mediating general sensations are located in the skin and the connective tissues of muscles, tendons, joint capsules, and viscera of the thorax and abdomen. A basic understanding of general sensations and special sensory physiology begins with defining sensation and its attributes. These are followed by consideration of the structure of receptors, the nature of the receptor discharge in response to a stimulus, processes of information coding, peripheral and central sensory pathways, and processing of sensory information within the central nervous system (CNS).

2.1 Attributes of Sensation

A sensation is what is perceived in the brain when a sensory receptor or, more commonly, a group of sensory receptors are stimulated. Many sensations, such as pain or heat, are of a conscious nature, whereas others, such as blood pressure or muscle stretch, may not reach the conscious sphere. Sensations also differ in various other ways, such as in modality, quality, and quantity (Rhoades et al., 2003). Modality is the characteristic that distinguishes one type of sensation from all other types. Sensations of the same modality may differ qualitatively. Sensations of the same modality and quality also may differ quantitatively. The perception of sensory stimuli is a complex process involving various sensory receptors; peripheral and central neural pathways; interactions between components of the pathways.

2.2 Sensory receptors

For the body to react in a purposely manner to changes in the external and internal environments, the CNS needs information concerning the nature of the environmental change. Such information is generated by specialized structures that receive stimuli and therefore are called sensory receptors. In some cases, the sensory receptor is a bare or free nerve ending; in other cases, the sensory nerve ending is encapsulated. In more complex sensory structures, such as the eye or the ear, stimuli are detected by specialized sensory cells that are not neurons but can relay the stimulus information to sensory neurons (Bear et al., 2001).

2.2.1 Classification of Sensory Receptors

Sensory receptors may be grouped into two major categories: exteroceptors and interoceptors (Rhoades et al., 2003). Exteroceptors detect changes in the body's external environment. Interoceptors detect changes in the body's internal environment. Receptors also may be differentiated on the basis of structure, location, or modality of sensation. The first basic function of a sensory receptor is to detect a change in the environment, called a stimulus, and convert the energy (e.g. heat, light, pressure, and so on) of the stimulus into electrical signals in the nervous system. This conversion process is known as transduction. All sensory receptors are transducers; they respond to an adequate stimulus by generating a series of graded potentials or nerve impulses in their associated afferent nerve fiber.

Some sensory receptors (Fig. (1)), such as the Pacinian corpuscle, are encapsulated nerve fiber terminals (Rhoades et al., 2003). When an adequate stimulus (pressure) is applied to the Pacinian corpuscle, the ion permeability of the nerve ending to Na^+ is increased, allowing Na^+ to enter the fiber terminal and decrease the membrane potential (Fig. (2)). The resultant small, temporary change in the membrane potential is called a generator potential. The generator potential in turn induces, via current flow, depolarization of the first node of Ranvier. If the generator potential is of sufficient amplitude to bring the first node to threshold, an action potential is generated and a nerve impulse is propagated along the fiber. The amplitude and duration of the generator potential is directly proportional to the intensity and duration of the applied stimulus and determines the frequency of firing (number of impulses conducted per second) of the afferent fiber.

Many receptors, with the notable exception of free (bare) nerve ending that mediate pain, respond to the continued application of constant-intensity stimulus with a decrease in the magnitude of the generator potential or the receptor potential, in the other words, a return toward the resting membrane potential. The decline in the generator potential or receptor potential in response to maintained receptor stimulation is called adaptation or accommodation. When adaptation of the receptor is complete, sensation is no longer perceived from the receptor until the intensity of the stimulus is changed. With no adaptation, such as displayed by pain receptors, a maintained stimulus produces an undiminished sensation. Some receptors adapt very rapidly and are therefore more useful in signaling a change in frequency of stimulus application rather than a change in stimulus magnitude. These receptors are called phasic receptors or velocity receptors. Some pressure receptors that detect vibration and hair-ending plexus in the skin are examples of phasic receptors. Receptors that adapt very slowly or not at all are called tonic receptors or intensity receptors. Pain receptors and some stretch receptors of muscles, tendons, and ligaments are examples of tonic receptors. In general, tonic receptors provide continual information as long as the stimulus is being applied or until the receptor eventually adapts.

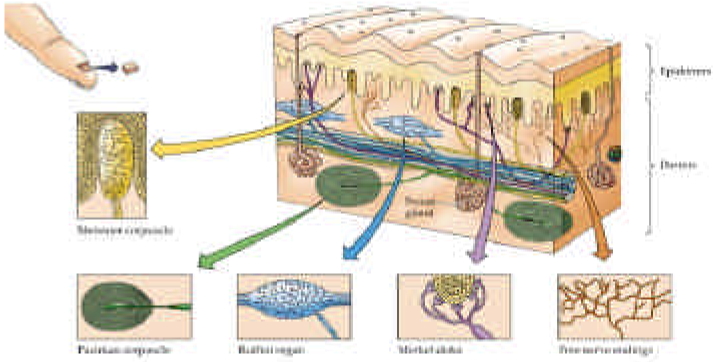

Figure. 1 Somatosensory receptor in the skin (Wisconsin-Madison, 2002)

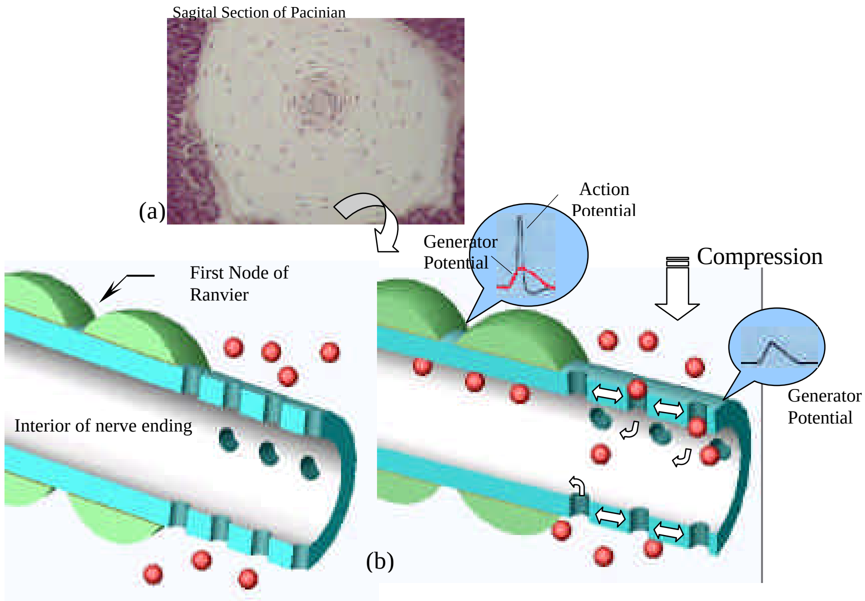

Figure 2. (a) A Pacinian corpuscle, an example of sensory receptor for touch, consists of a neuron wrapped in layers of connective tissue, with a myelinated nerve ending (axon). (b) A tactile (pressure) stimulus causes the neuron within the connective tissue to change shape, allowing Na^+ to enter the cell. Pressure stimulus produces a depolarizing generator potential and an action potential.

2.2.2 The adequate stimulus and specific nerves energies

Specific types of sensory receptors are more sensitive to certain types of stimuli. The type of stimulus (modality) to which the receptor is most sensitive, that is, for which the receptor has the lowest threshold, is called the adequate stimulus. Nearly all receptors respond to stimulus intensity is great enough. For a receptor to respond, the stimulus strength must exceed a certain minimal (threshold) value. The threshold strength of a stimulus is lowest for the adequate stimulus, and higher for other types of stimuli.

Regardless of the type and strength of a stimulus applied to a given receptor, the sensation perceived when the receptor responds is always the same. This phenomenon is known as the law of specific nerve enegies (Muller’s law) (Rhoades et al., 2003). The interpretation of Muller’s law must be general rather than strict because there are sensations that we perceive because of the simultaneous simulation of two or more receptors sensitive to different modalities of stimulus.

2.2.3 Information Coding

Sensory information comes to the CNS in the form of nerve impulses. The CNS decodes and interprets or reacts to the incoming information. Decoding of sensory information is based: on the location of the receptor, the adequate stimulus for the receptor, the frequency of nerve impulses being transmitted by the afferent fiber associated with the receptor, the number of receptors activated by a stimulus, and the central pathway (Rhoades et al., 2003).

The size of the action potential generated in the afferent fiber associated with a sensory receptor does not vary with the intensity or duration of the stimulus applied to the receptor. Therefore, the amplitude of the action potential cannot be used to code information about the nature of the stimulus. However, the frequency with which action potential are generated does vary according to the magnitude of the stimulus intensity, summation of successive generator potentials, and adaptation of the receptor. Information about stimulus intensity and its rate of change therefore may be coded in the form of nerve impulse frequency, this is known as the frequency code of stimulus intensity.

The type of information sent to the brain also is coded in the way that nerve fiber pathways leading to the brain are arranged physically. The information about temperature of the skin reaches the brain by a different nerve fiber pathway than does information about pressure. In this way, information about the quality, or type, of stimulus is maintained within each pathway without becoming mixed with other types of stimuli. This aspect of the nervous system, the mechanism of coding for the type of stimulus detected by a sensory receptor, is called the labeled-line code of stimulus quality (Fig. (3)).

2.2.4 Types of Somatosensory receptors

The types of somatosensory receptors include (1) tactile receptors, activated by mechanical stimulation of the body's surface; (2) thermal receptors, activated by changes in temperature on the surface of the body; (3) nociceptors, or pain receptors activated by noxious (harmful) stimuli; and (4) proprioceptive receptors activated by movement of the limb.

Tactile receptors are called mechanoreceptors. These receptors are responsible for detecting touch, pressure, and vibrations applied to the skin. Five types of cutaneous receptors that provide for a sense of touch, pressure, stretch, or vibration, are the Merkel's discs, Meissner's corpuscle, Ruffini corpuscle, and hair-follicle plexus.

The hair-follicle receptor is a hair follicle on the surface of the skin and has a bare nerve fiber wrapped around its base. The bending of the hair shaft produces a mechanical displacement of the nerve fiber at the base of the follicle. This displacement, in turn, opens Na^+ channels, resulting in a generator potential and the initiation of action potentials. The hair-follicle plexus is the most sensitive, responding to very small deformations of the protruding hair, and is also the most rapidly adapting touch receptor.

Meissner's corpuscle is an elongated, encapsulated receptor found in the dermis of the skin close to the epidermis. The adequate stimulus for Meissner's corpuscle is light touch or pressure, such as that experienced when stroking the skin with a feather. Merkel's discs also respond to light touch, are more sensitive than Meissner's corpuscle, and are the only touch receptors in the epidermis of the skin. A single nerve fiber supplies many discs, and each disc is located below an epithelial cell. Pressure on the epithelial cell stimulates the disc below, resulting in a sensation of very light touch.

The Pacinian corpuscle is the largest, most widely distributed receptor, detecting heavy pressure. It is located deep in the dermis of the skin and is prominent in skin of the hands and feet, as well as in joints, ligaments, the wall of many viscera, membranes of the mesentery and peritoneum, connective tissue of the muscles, and elsewhere. Pacinian corpuscles have a much higher threshold for pressure stimuli than other touch receptors. In addition to pressure, however, the Pacinian corpuscle is capable of detect vibrations. The mechanisms that allow it to detect vibrations are extensions of its ability to rapidly adapt to applied pressures.

When the pressure is applied to the Pacinian corpuscle for a length of time, it quickly stops generating action potentials. This occurs when the Pacinian nerve ending reverts back to its original shape even though the outer lamellae of the corpuscle remain distorted. As the applied pressure is released, the layers of connective tissue surrounding the nerve ending spring back to their original ellipsoidal form and then become compressed again in the opposite direction because of the elastic nature of the connective tissue. This recompression deforms the nerve ending and again causes Na^+ channels to open and produce a generator potential and action potentials. In this way, both application and release of pressure result in the discharge of action potentials.

The Ruffini corpuscle is slowly adapting, tactile mechanoreceptor that continues to generate action potentials as long as the stimulus is applied. This receptor is sensitive to stretching of the skin, such as that produced during a massage.

Nocireceptors are free nerve endings that detect painful stimuli. In general, two types of nociceptors are mechanical, activated by intense mechanical stimulation, and heat, which respond to temperature above 45°C. Pain receptors are the simplest, least specialized of receptors consisting of bare or free nerve ending (dentrites) of nonmyelinated sensory neurons. Compared with other types of cutaneous receptors, pain receptors have much higher threshold and respond to many modalities of stimulus (e.g. chemical, thermal, mechanical, and so on).

The position of the body's limbs is detected by proprioceptors. A static proprioceptor detects the stationary position of the limbs in space with respect to the other parts of the body. A dynamic proprioceptor transmits information about ongoing limb movement to convey the sense of movement. The brain needs this information to determine where the limb is located and how quickly they are moving in order to calculate how much further they need to go to complete a certain movement. The sense of stationary or static position is transmitted to the brain by mechanoreceptors located in joint capsules, cutaneous mechanoreceptors, and mechanoreceptors in muscles that are specialized to transducer the stretching of the muscle. Receptor types include the annulospiral and flower-spray ending of the neuromuscular spindle and the Golgi tendon organ. The static proprioceptors produce a continuous frequency of action potentials in response to different joint positions. If the joint is left in one particular position, the receptor generates action potentials at one specific frequency. This type of action potential response is called a tonic discharge. The dynamic proprioceptor generates action potentials only with change in direction of movement. The burst of action potentials produced is very brief. This type of action potential response is called a phasic discharge.

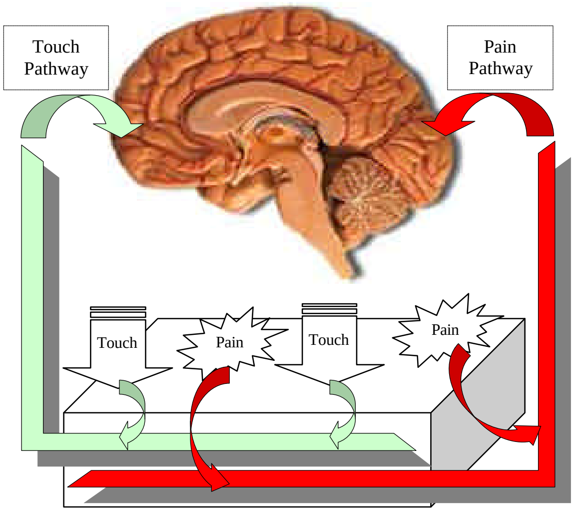

Figure 3. The labeled-line code of stimulus quality. Although different stimuli affect the skin, each type of stimulus has its own pathway to the brain, ensuring clarity of sensory messages.

The information from somatosensory receptors is transmitted to the spinal cord and brain by several different pathways organized according to the following general principles: (1) somatosensory pathways from the receptor to the cerebral cortex are made up of three neurons arranged in sequence; (2) each type of somatic sensation has a specific defined pathway; (3) most pathways cross over from one side of the spinal cord or brain to the other; (4) all spinal nerves and cranial nerves are paired, and each member of the pair, designated right or left, is distributed unilaterally, and somatosensory pathways are paired and are designated right or left, based on the position of the ascending axons in spinal cord (for pathways originating with spinal nerves); (5) the nerve cells within each nucleous are topographically organized according to the location of their sensory receptors on the surface of the body. Second-order neurons transmit the signal further up the spine and into the thalamus region of the brain. Here third-order neurons complete the path to the somesthetic area of the cortex where the corresponding sensations of pressure, temperature, or pain are registered.

3. Haptics Devices Model

In recent years, interest in haptic perception has increased because of the development of man-machine systems such as telemanipulators and interactive human-computer systems. The desire for natural, intuitive means of human-machine interaction and for multi-modal sensory feedback to users has resulted in the design of machines which allow users to generate control inputs using hand motion, and at the same time experience forces or resistance on their hands which create interesting and useful perceptions. These machines are called haptic interfaces. They are typically robot-like mechanisms with rigid handles, which are able to move in one or more degrees of freedom. Important system components include actuators, motion and force sensors, and a digital controller.

At present, haptic interfaces are still mainly confined to research and development facilities because they are expensive and difficult to program. They are generally used in two contexts: telemanipulation and computer simulation interaction (i.e. virtual environments). A system for telemanipulation with force feedback is shown in Fig. (4).

Telemanipulation is a scheme in which a “slave” robot arm, usually in remote or dangerous environment, tracks the motion of a “master” manipulator. The human operator physically interacts with the haptic interface, exchanging mechanical energy with it. Motion of the haptic interface is transducted and scaled by K_{ms}. The result is sent to the slave manipulator as a motion command. The slave manipulator moves in synch with the operators’ motions, performing work on the environment. The forces of the interaction between the slave and the environment are in turn measured, scaled, and sent back as force commands to the haptic interface. This architecture is known as position/ force control, it will be explained in more details in the next item.

Certain details of a real system might be different from that shown in Fig. (4), for example velocity and force signals might flow in the opposite direction, but the basic idea is the same: the impedance of the haptic interface is controlled to be similar to the impedance encountered by the slave manipulator manipulator. Mechanical impedance is defined as the dynamic (history-dependent) relationship between the motion input to a system, and the force output from the system, where the instantaneous product of velocity and force is the power being transferred between the systems that are interacting.

Figure (5) is a block diagram for haptic interface to a computer simulated (virtual) environment. In this system a signal representing the motion of the haptic interface is input to a computer simulation of a mechanical environment, which computes a desired reaction force. The system is similar to the telemanipulation system, except that the interaction between the slave robot and environment is simulated with a computer algorithm. Again the input and output signals to the simulation could be reversed.

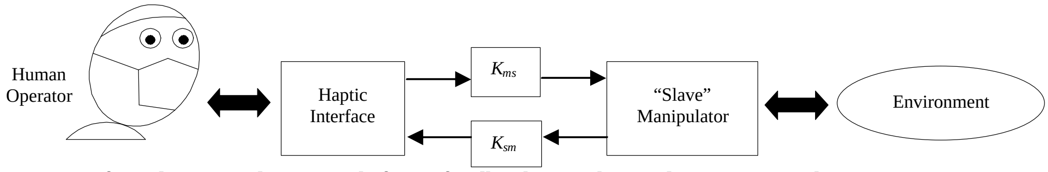

Figure 4. System for telemanipulation with force feedback. Mechanical connections between components are shown as single thick line with a double arrow, indicating bilateral interaction. Signal connections are shown as two separate lines with single arrows, indicating that each signal flows in only one direction.

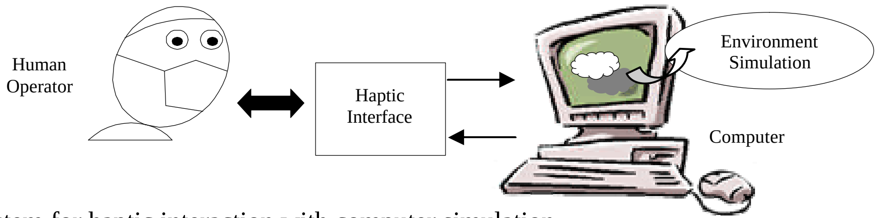

Figure 5. System for haptic interaction with computer simulation.

3.1 Actuators for Haptics

In haptics interfaces, the used actuators must have the capability to accomplish the required forces and torques to give the tactile sensing feedback to the user. If the actuators are not used, the haptic system just works as an environmental sensor. Therefore, the actuators are also important part of the haptic devices. There are several actuators types that can be used to feedback in haptic systems, these actuators can be the classical electric motors, hydraulic pistons and pneumatic muscles until the novel and innovative, as the artificial muscles (shape memory materials), magnetostrictive, piezoelectric motors, polymeric gels and metal hydrades (Burdea, 1996). These last ones are still being studied for future applications.

The choice of the most appropriate actuator to each application is based on its functionality, control and general parameters of performance, as the maximum force or maximum torque of output, the sustained forces and torque, consumption of energy and bandwidth. The actuators should present certain specific characteristics as the master manipulator must be light enough to minimize user's fatigue, but powerful enough to apply significant forces to the environment. The actuators should maximize the power-to-mass ratio. As the number of joints increases more actuators are necessary with a high power-volume ratio. The ideal interface needs to be transparent, what means that the user only feels the applied force from the environment's interactions, and the actuators should be capable to make the master to follow the movement of the user's hand quickly and without opposition (backdrivability).

Different types of actuators can be used for haptic devices. The most used are the electric motors and the main characteristics are: easy installation, cleanliness (no oil leaks), noise emission and easy control. The DC motors are especially used in this application due to their size, weight and controllability. The DC motors can be brushed or brushless. There are three different types of field-circuit connections for brushed DC motors: series, shunt and compound. While the connection in series presents the highest initial torque and it is used in low speeds and applications that demand high torque, as in haptic interfaces, the brushless DC motors present as main advantage low mechanical impedance, once they don't have brushes and therefore they present low friction. When compared to the Brushed motors, they present disadvantage of an additional position sensor, increasing its volume, and have to produce a rotative magnetic field, making their control complex.

A novel actuator called Shape Memory Alloy (SMA) that presents mechanical memory effect has been largely used because its great characteristics to haptic applications. This characteristic is caused by a structural transition between a martensitic and an austenitic phase caused by the heat generated by Joule Effect. When it happens, the alloy change its form to one that was before determined. This characteristic products tensile forces and when the current is interrupted the SMA wire cool down. The SMA wires present large forces and small deformation, while the SMA springs present small forces and large deformation. The main advantages presented by these actuators are: (1) don't present gears or other movable parts (it facilitates the maintenance); (2) present greater power-weight ratio than the one of the electric motors; and (3) compactness. The actuators with these characteristics are easily applied to haptic systems. One of the applications in haptic system that has already been done is a tactile feedback array that use SMA wires and are placed at the user's fingertip (Burdea, 1996). Their disadvantages are: (1) the actuators cool down slowly turning slow the return movement; (2) low energy efficiency; (3) high power consumption; (4) great dissipation of energy in form of heat, turning the apparatus uncomfortable for the user.

The pneumatic actuators also can be used in haptic applications because its cleanliness and safety, what make it useful in medicine. The pneumatic actuators present smaller force (torque) exertion capabilities than the hydraulic actuators. Their main advantages are: (1) a lighter construction than the hydraulic ones, what results in a high power-weight ratio superior to that of electrical actuators; (2) the technology is simpler and much cheaper than hydraulics, therefore, are easier to install and operate. But it have their drawbacks: (1) air is compressible, what turns the system stiffness response and the bandwidth lower than for hydraulic actuators; (2) high friction losses caused by the absence of lubrication (air is not self-lubricating) and others.

The pneumatic actuators used in haptic interfaces have various configurations, such as micro bellows (miniature inflatable air pockets-are placed in fingertip arrays or in palmar area in gloves producing tactile sensation) (Stone, 1991), linear pistons, rotary motors or braided inflatable tubes and pneumatic muscle actuators (PMA) (Burdea, 1996).

3.2 Sensors for Haptics

Sensors are used to provide the essential information about the area of contact and the resulting forces and torques measured at this interface. A complete touch sensory system must contain the following elements (Russell, 1993): skin-like touch sensors; some form of robotic manipulator/gripper; sensors to measure the forces/torques acting on it; and the intelligence to plan the gathering and interpretation of touch sensory information.

Some characteristics should be observed when selecting or designing a sensor, determining its action in the system to which is applied. The characteristics are range, resolution, precision, sensibility, error, and the frequency response. The frequency response is important due to the fact that several stimuli cannot be detected because of the sensor frequency range limitation. The absolute difference between the real value of the pattern and the value obtained from the sensor, are also important (Lee et al., 1999). This last characteristic is used broadly in the control of robotic systems (Madhani, 1998).

The tactile sensing can be divided in two different groups: the extrinsic and intrinsic sensing, as in the human haptics. The extrinsic sensors are devices that interact with localized regions and are mounted at the contact interface. Therefore, the intrinsic sensor refers to the derivation of contact data from force sensing within the mechanical structure of the system. Force sensing produces information such as contact vectors and point locations. An example of intrinsic sensor in haptics is a six axis force sensor built on the base of a link in a manipulator. This sensor is mounted into the structure of the robot and does not depend on the external stimuli.

The position of the manipulator or gripper can be obtained by the use of different kinds of sensors, e. g., resistive (potentiometer), encoders, capacitive, inductive, electric, other ones are synchros, resolvers, linear and rotative inductosyns (Werneck, 1996). This information is essential for the exact displacement of the manipulator and its control. The more frequently used sensors to measure the forces and torques in the robotic devices, are the strain gauges. The piezoelectric sensors are also used and function like the strain gauge, but they generate a voltage when submitted to a pressure. Another one is the capacitive sensor that changes the voltage with the variation of the distance between the plates (Russell, 1993).

Skin-like touch sensor, which is designed to mimic the human skin, consists, basically, in a contact sensor array that measure contact forces and still offer some surface information. To measure forces, the sensor must contain a deformable element that deforms depending on the applied force, and some technique can be used to measure such deformation. The acting of this deformable element has big influences in the characteristics of the sensor.

The simplest kind of contact sensor is an on-off switch, but it provides only a limited amount of information and therefore is not usually favored. The piezoresistive sensors are the most used for contact sensor arrays that in its simplest form a piece of piezoresistive material is sandwiched between electrodes and the resistance between them is related to applied force. These sensors are cheap, simple to construct and give a large electrical output. There are other kinds of contact sensors, e.g., piezoelectric polymers that a pressure is applied to a crystal and its mechanical deformation result in a voltage signal (excessive temperature destroys their properties).

3.3 Control Study

The control architecture for haptics devices can be studied by the variables types (position, force, velocity, and so on) and by the direction of the flow control, which means the control is from master to slave or vice versa. For example, the position/force control represents that the master's positions are sent to the slave and the slave's forces are sent to the master. In simulation systems as the slave side is replaced by the virtual scene the variables and action are controlled by an algorithm. An example of this, it's the haptic interface developed by Baumann for minimally invasive surgery simulation at the Swiss Federal Institute of Technology (Baumann et al., 1998). These control architectures are also used in diverse fields of teleoperation, as space control and underwater control. In the most part of the teleoperation systems found, the variables used for the control are the common error between master's and slave's ones.

In this manner, methods of controlling a force reflecting master/slave system include position/position, position/force, force/position, force/force, and full bilateral servo control (Taylor, 1993; Kwon et al., 1999). In position/ position system the slave is commanded to the position of the master, as for the unilateral system, but the master is also commanded to drive to the position of the slave. If the actuator forces are proportional to the position error signal then representative force representative force reflection is achieved. This is a mechanically simple system requiring no force transducers but has disadvantages of low accuracy and resolution together with the problem that any movement will cause an error signal and hence a force which results in an unwelcome “viscous” feeling to the movements. Strategies to overcome this problem, such as velocity feedforward, tend to result in complexity in the software, which offsets the inherent simplicity of the system.

A position/ force system works by driving the slave to the position of the master and driving the master with forces proportional to those encountered at the slave. The “viscous” feel problem is avoided by this method but force transducers are required at the slave and problems of stability can result due to the master and slave being controlled by different methods. System gains and hence overall performance may therefore be limited. This method is considered for many researchers due to the high bandwidth of force feedback (Kwon et al., 1999). A robust position controller on the slave manipulator helps to mask internal friction and the use of the contact force sensed at the slave provides a higher quality force reflection to the operator. Generally, the master should have low inertia and high back-drivability to avoid distortion of the operator’s perception, as the system designed Kwon at KAIST (Korea) a PD controller with a disturbance observer (Kwon et al., 1999). A PD controller is the most used in this field as it will shown, for example it was used by Benali at the Laboratoire de Robotique de Paris in their force feedback interface (Benali et al., 1999). Other robust control systems as adaptive controller can be used. For example, Ando at University of Tokyo implemented the adaptive controller for the haptic interface in tele-micromanipulation (Ando et al., 2001).

Bilateral force reflection systems are essentially symmetrical that means, that a force applied at the slave produces a force at the master and vice versa, with joint positions and velocities also included in the control algorithms. Gravity compensations may also be incorporated to reduce operator fatigue problems.

Another classification of the architecture models found in the literature is the impedance and admittance types (Sirithanapipat, 2002; Burdea, 1996). The impedance model involves the manipulation of positions and/or velocities variables, having a computer algorithm to calculate the output forces to the manipulator. Most haptic interfaces that use impedance displays, require only an actuator with position or velocity sensor. At the other side the admittance model deals with forces and/or torques variables, and an algorithm will define the output positions to the manipulator. Such kind of method is usually used in a heavy industrial robot, since these are non-backdrivable. Because of the force input necessity, an expensive force sensor is required for the admittance type of haptic system.

In spite of these architectures some researchers opt for other schemes, as the system developed by the Berkeley University, San Francisco University and the Endorobotics Company for their *Telesurgical Workstation* (Çavusoglu, et al., 1999). They separated the position control and the tactile display, in this manner the operator that makes the link between his sensations and the position of the manipulator.

Niemeyer represented in his thesis (Niemeyer, 1996) the master/slave manipulators as pure inertial elements connected by a spring and a damper, and with that he didn’t need of force measurements as in the position/ position models. This system could be defined as a PD controller with the spring constant representing the gains for the common position errors and the damper constant the gains for the common velocity errors. Niemeyer applied his methodology to the control of Silver and Black Falcon telesurgical systems designed by Madhani at MIT (Madhani, A.J., 1998). In these systems, they didn’t treat another main issue in teleoperator systems: time delay. In short distances (theatre field) as they worked with this delay was not a great problem. This spring and damper model was also applied by other researchers and in other application out of surgery area. Baumann used this model with the addition of a bias force to simulate static forces in his surgical haptic interface (Baumann et al., 1998). In the space industry, this model was implemented by the DLR (Deutsches Zentrum für Luft- und Raumfahrt) in Germany in the ROTEX (Roboter Technology Experiment) system (Hirzinger et al., 1997). They implemented a predictive control using a simulated environment to overcome time delay issues and avoid operator’s mistakes.

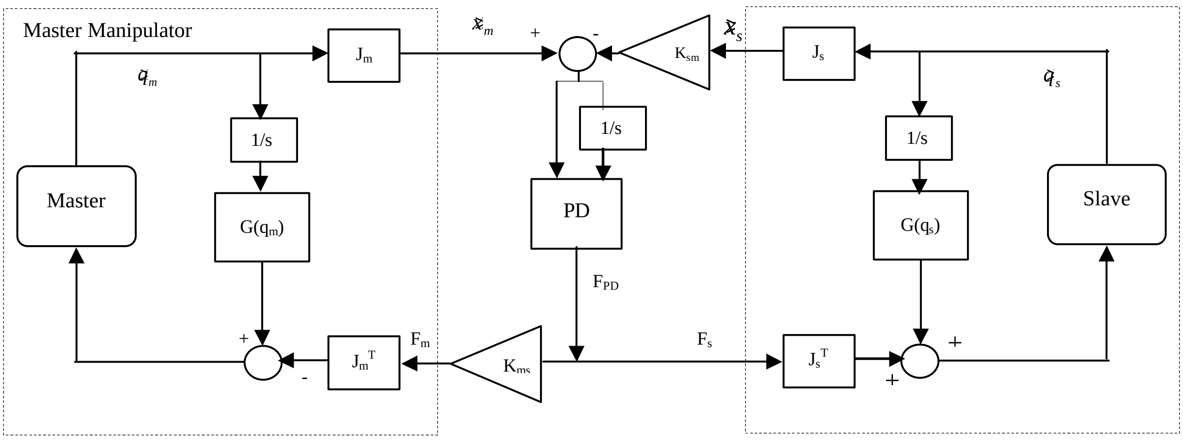

Figure 6. Control overall system: J_m and J_s represent the master’s and slave’s manipulator Jaccobian matrixes; $G(q_m)$ and $G(q_s)$ are the gravity compensations matrixes; q_m and q_s are the Joint space coordinates; and x_m and x_s are the Cartesian space coordinates.

Fig. (6) presents the overall system designed for our system. As the system was design to work in the surgery room, time delay compensations were not implemented. Scaling variables K_{sm} and K_{ms} are defined to increase the user´s perception of slave motions and forces and to allow the user to work in small sites.

4. Conclusion

This paper discussed the models of haptics system in the human beings and devices for medical applications. Although these models can be used in further applications as in the space and underwater. Comparing the models, it can be noticed that both have similar parts in their transduction and behavior. Haptic devices help to extend the medical robot capability to transmit to the surgeon sensation of the surgery site (real or simulated). Sensations lost in the traditional minimal invasive surgeries can be replicated and scaled with these devices. The control in haptics involves the coordination between master and slave devices. The spring and damper model was chosen by its facility to be implemented, though more robust controls can be used, e. g., fuzzy controls.

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6. References

Ando, N.; Morioka, K.; Szemes, P.T. and Hashimoto, H. “Development of 6 DOF Haptic Interface for Tele-micromanipulation Systems” IECON´01: The 27th Annual Conference of IEEE Industrial Electronics Society, pp.444-449, 2001

Bear, M.F.; Connors, B.W. and Paradiso, M.A. "Neurociências: desvendando o sistema nervoso" 2nd edition Ed. Artmed, 2001

Benali, A.; Richard, P. and Bidaud, P. “Design, Control and Evaluation of Six DOF Force Feedback Interface for Virtual Reality Applications” Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 338-343, 1999

Burdea, G.C. “Force and Touch Feedback for Virtual Reality” Wiley-Interscience, 1996

Çavusoglu, M.C.; Tendick, F.; Cohn, M. and Sastry, S. S. “A Laparoscopic Telesurgical Workstation” IEEE Trans. on Robotics and Automation, Vol. 15, No. 4, pp.728-739, 1999

Faraz, A. and Payandeh, S. “Engineering approaches to mechanical and robotic design for minimally invasive surgeries (MIS)” Kluwer Academic Publishers, 2000

Green, C.D. “Classics in the History of Psychology” York University, 2002

Hirzinger, G.; Brunner, B.; Koeppe, R. and Vogel, J. “Advanced Telerobotics” ARS’97 Advanced Research Workshop “Autonomous Robotic Systems”, 1997

Kwon D-S; Woo, K.Y., Cho, H.S. “Haptic Control of the Master Hand Controller for a Microsurgical Telerobot System” Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 1722-1727, 1999

Lee, M. H., H.R.Nicholls, 1999, “Tactile Sensing for Mechatronics – a State of the Art Survey,” Mechatronics vol.9, pp 1-31

Lima, F. J. and Silva, J. A. “Algumas considerações a respeito do sistema tátil de crianças cegas ou de visão subnormal” in O Tato, 2002

Madhani, A.J. “Design of Teleoperated Surgical Instruments for Minimally Invasive Surgery”, Ph.D. Thesis Massachusetts Institute of Technology, 1998

Millman, P.A. “Haptic Perception of Localized Features” Ph.D Thesis Northwestern University, 1995

Niemeyer, G. “Using Wave Variables in Time Delayed Force Reflecting Teleoperation” Ph.D. Thesis Massachusetts Institute of Technology, 1996

Rhoades, R. and Pflanzer, R. “Human Physiology” 4th edition Thomson Books/Cole, 2003

Russell, R. A., “Giving Robots a Sense of Touch: An Overview” in Robots for Competitive Industries, 1993.

Sheridan, T.B. “Human and Machine Haptics in Historical Perspective” in HMH’97 Workshop on Human and Machine Haptics, 1997

Sirithanapipat, T. “Haptic Interface Control Design for Performance and Stability Robustness” Ph.D. Thesis Vanderbilt University, 2002

Taylor, A.J. “Design Issues for Underwater Manipulator Systems” Mechatronics Vol. 3 No.4 pp.419-432, 1993

University of Wisconsin-Madison / Dept. of Physiology website URL: http://www.physiology.wisc.edu/ Accessed in December 2002

Werneck, M. M., “Transdutores e Interfaces,”Livros Técnicos e Científicos Editora, 1996.