Chapter 1

Introduction

1.1 Motivation and objectives

The perception of the state of complex systems by an operator can be a huge challenge, either by the number of Degrees of Freedom or by the way that information is conveyed to the operator senses. That is particularly relevant in robotic teleoperation and robots with several degrees of freedom, but also in the evaluation of effort states, pain or discomfort of human beings in physical exercise like, for example, in medical rehabilitation. Thus, it is proposed to develop a haptic interface that allows the operator to have a richer perception of a complex system state, like a robotic system or even some electromyographic parameters, or similar, of a human being in therapeutic rehabilitation processes.
For that, it is necessary to develop an equipment that allows the perception by contact in an area of the operators body that somehow reflects one or more extern quantities. That external information can come from real or simulated sensors, connected to a human patient or a robotic system, like humanoid robots, or even simpler, from simulators.
These sensations in the operator can transmit a big wealth of information and can complement other traditional perception processes like vision or hearing.
The stimulus in the operator can be created in several ways like contact, temperature or electro-stimulation. In this project, it is proposed to explore essentially a contact form based in vibrations with adjustable intensity.
Therefore, the development and use of a network or a mesh of distributed vibration motors in a support to place, for example, in the arm of the operator, will be explored.
In Robotics this sensations can translate mechanical efforts, movement resistance, current consume, force sensors in robots, etc. In the human being they can translate position states, cutaneous pressure or muscular effort (by electromyography, body temperature, etc), or just simply create sensations that can emulate states or perception contexts for virtual reality or immersible multimedia experiences like multidimensional cinema.
To summarize, the main objectives for this project can be defined as the following:

- Development of a control system for a network of mini vibration motors;
- Development of a usable prototype so that the haptic interface parameters effects can be tested in a human being;
- Definition and test of variable stimulation patterns to translate specific informations

of an external system.

1.2 State of the Art

1.2.1 Principles of Haptic

Traditionally there are five perception methods, the famous five senses: palate, vision, smell, hearing and touch. With the absence of some of these senses, very simple tasks like standing, walking, seating, grabbing an object and writing can become very tricky. It is known that patients with total loss of their tactile senses are unable to drink out of soft plastic cups since they are unable to grasp and hold to the cup. Furthermore, when we place an object on a surface we combine information from our memory regarding the weight, compliance of the object and the friction of the surface [1] with the information we receive from our tactile sense and our visual sense (for example the distance between the object and surface). [2]
Touch is the first sense to develop in infants [3] and Thomas Aquina said in *De Anima* that, without the possibility of touch, no other sense could exist: touch is «the first sense, the root and ground, as it were, of the other senses» [4], defining touch as the most important sense of all.
Even thought that in modern times vision is considered the dominant sense, the touch continues to be important to the human behavior.[5] To this sense of touch the concept of haptic is associated.
The term *haptic* comes from the Greek word *haptikos* which means being able to lay a hold of, be able to perceive, to grasp. [6] Since the early 20th century, psychologists have been using this term to label the subfield of their studies that addressed human touch-based perception and manipulation. [7]
In 1892 Max Dessoire introduced the concept of haptic as "the science of the human touch". [8]
In 1966 Gibson defined it as "the sensibility of the individual to the world adjacent to his body by use of his body". [9]
In the 70s and 80s, the robotic community also began to focus on manipulation, perception and interaction by touch. [10]
Haptic also includes kinesthesia, also known as proprioception, which is the ability to perceive ones body position, movement and weight, therefore becoming common to designate the sensory motor components of haptic as the haptic channel. [11]
In the 90s the technology had improved and a new type of haptic began to emerge: the virtualized haptic (computer haptic). As the name indicates, this is no more than a virtual environment where the user can feel by applying forces, vibrations and/or motion on the user. This mechanical simulation may be used to assist in the creation of computed virtual objects that can be physically palpated and controlled and also to allow remote control of machines and devices.
This new sensory display modality presents information by exerting controlled forces on the human hand through a haptic interface, rather than, as in computer graphics, in the form of visual and auditory signals. [12] Unlike computer graphics where audio and visual channels feature unidirectional information and energy flow (system to user), haptic interaction is bidirectional as humans send and receive haptic signals.[13]
Figure 1.1 is a small scheme of the subsystems and information flow related to the in-

teractions between users and haptic interfaces. On the right side there is the dynamical system of the haptic interface with a computer, and on the left side there is a dynamical system of the user with the central nervous system. [14]

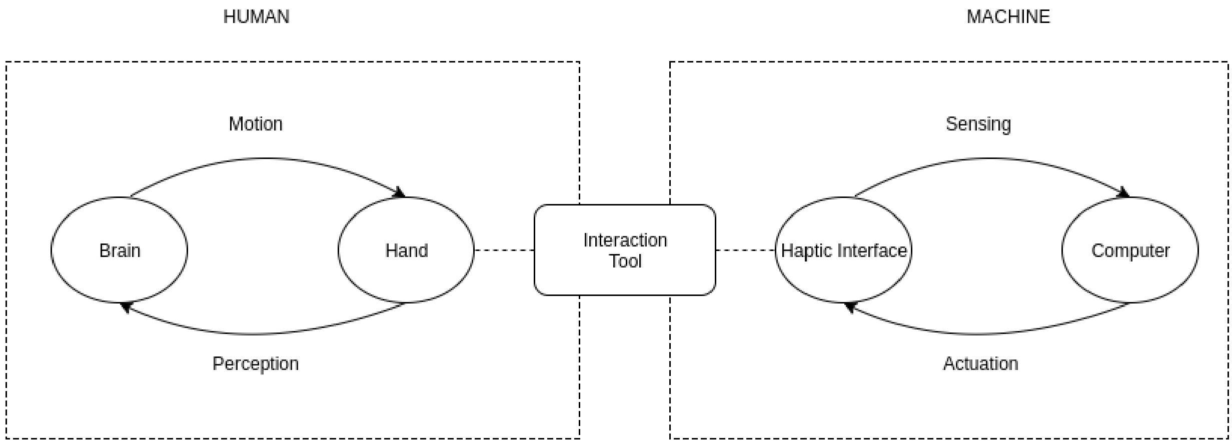

Figure 1.1: Haptic interaction between humans and machines (adapted [14])

- *Human sensorimotor loop:* when a human user touches a real or virtual object, forces are imposed on the skin. The associated sensory information is conveyed to the brain and leads to perception. After interpreting the environment, the brain motor commands activate the muscles and result in hand and arm motion.
- *Machine sensorimotor loop:* when the human user manipulates the end-effector of the haptic interface device, the position sensors on the device convey its tip position to the computer. The models of objects in the computer calculate in real-time the torque commands to the actuators on the haptic interface, so that appropriate reaction forces are applied on the user, leading to tactual perception of virtual objects.

Virtual reality technology allows the user to interact with computer simulated objects in real time and under real or imaginary conditions, and it is one of the technologies where haptic is the most useful. It is used in gaming but also in medical (Section 1.2.4), robotics (Section 1.2.2) and graphical art applications. [15]
Application's main elements include:

- *simulation engine*, responsible for computing the virtual environment's behavior over time.
- *visual, auditory and haptic rendering algorithms*, which compute the virtual environment's graphic, sound and force responses toward the user.
- *transducers*, which convert visual, audio, and force signals from the computer into a form the operator can perceive.
- *human operator*, who typically interacts (bidirectional) with the haptic interface device and perceives audio and visual feedback , from computer, headphones, visual displays, etc.

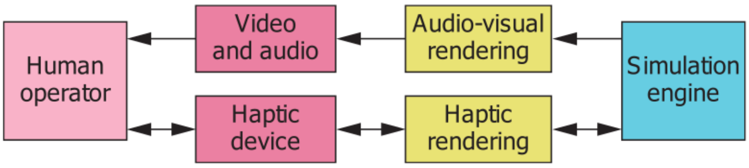

Figure 1.2: Basic architecture for a virtual reality application incorporating visual, auditory and haptic feedback[12])

Being able to touch and manipulate objects in an environment, in addition to just seeing or hearing them, provides a sense of immersion in the environment to the user otherwise not possible making haptic very important to the concept of virtual reality.
Currently there are already some gadgets that use the tactile perception channel as they send out vibratory signals. For example, the vibratory mode of mobile phones and rumble packs in gaming controls have been in our daily routines since a long time ago. [16]
Haptic is also used for example in the military, not only for military training and safety enhancement but also to analyze military maneuvers and operate vehicles. More, in cars and flight simulators the operator can also control the vehicle using for example a joystick and feel the feedback that it gives to the user.
Another example is in the medical training. Due to the contact haptic, it is possible the simulation of contact with organs which allows medicine students (and doctors) to practice for surgeries with an hologram and the touch sensation.
More advanced haptic interfaces make use of force feedback devices that can not only measure the position and contact forces of the user's hand, but also feedback position and force signals to the user.[17] Thus, haptic interfaces allows human-machine interaction through touch and mostly in response to user movements.

1.2.2 Robotic Teleoperation

Teleoperation is the technical term for the remote control of a robot at a distance. [18]
A teleoperation system allows humans to perform tasks that can be in an inaccessible environment without putting themselves at risk.
Usually a single operator is in control of the robot and feels some level of immersion in the remote environment [19].
In Figure 1.3 there is a teleoperation system set-up, with the operator environment and the teleoperator environment.

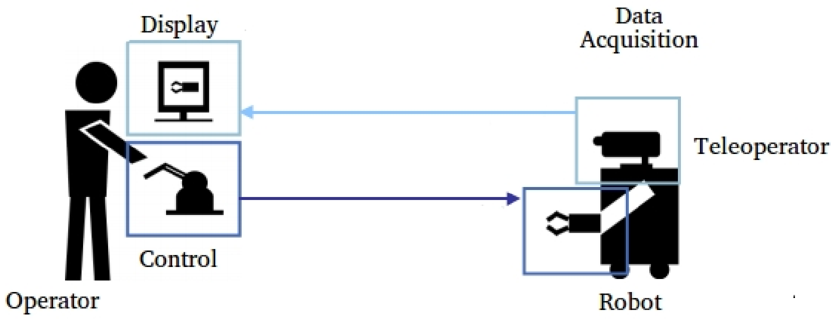

Figure 1.3: Teleoperation System (adapted [20])

As it can be seen in Figure 1.3, on the left, in the operator environment, a operator (human) interacts with the controls and displays comprising the human-machine interface of the operator device. A communication channel links the operator to the teleoperator device in the remote environment, where it controls the teleoperators manipulator via actuators. This actuator usually has clamps or grippers as an end-effector that interact physically with the objects in the remote environment. [16]
The industrial teleoperation systems have been around since the 50s when the Argonne National Laboratory developed a manipulation system with the aim of handling radioactive materials safely.[21] Later in the 60s a teleoperation system was also used in the US Army in the decommissioning of a nuclear warhead. [22] Both of this examples show how important robotic teleoperation is in the way that it allows the human being to do something that could be dangerous for its health, safely.
For instance, in the space industry the robotic teleoperation is also very used. There are several contributions of the US National Space and Aeronautics Administration (NASA) in that area, such as The Flight Telerobotic Servicer (FTS) program [23] and the NASA/NBS Standard Reference Model (NASREM). [24]
Even thought that in this past projects the robotic teleoperation was made without haptic feedback, currently there are already a few ones that use this technology.
One of those examples is the AILA robot (Figure 1.4). The DKKI (German Research Center for Artificial Intelligence) developed a system that allows to control a robot using an interface called CAPIO that simulates an exoskeleton at a distance of around 4000 km. As the operator is in Magnitogorsk in Russia, the AILA robot is in Bremen in Germany.
As the user moves, the CAPIO interface transfers those movements to the robot and returns haptic feedback of the robot movement. [25]

Figure 1.4: AILA with Operator [26]

Another example of a haptic system is the OCEAN ONE (Figure 1.5) developed by the University of Stanford. The OCEAN ONE is a underwater humanoid robot with haptic feedback that allows the researchers access to the deepness of the ocean, which use to be impossible for the human beings.
This robot is equipped with force sensors in each hand and, being controlled by an operator, thanks to the haptic feedback, this operator can feel the weight and shape of what it finds under the sea. [27]

Figure 1.5: OCEAN ONE [28]

On the medical department, with the increasing of the preference for non-invasive

surgeries, the surgeon stops having the perception and palpation that previously had with the conventional surgery.
Thankfully, there are already some tele-tactile feedback systems in which a sensor present in the equipment that the doctor is using, allows the recording of every aspect of the interactions with the tissues. Then, those details are processed and sent to the tactile display of a master robot.
One example of robotic teleoperation in medicine is the very well known Da Vinci robots (Figure 1.6).

Figure 1.6: Da Vinci Robotic Surgery System [29]

1.2.3 Nervous System

How we feel is associated not with our skin or our muscles but instead with our nervous system. It basically a collection of nerves (cylindrical bundles of fibers that start at the brain and central cord) and specialized cells (neurons) that transmit signals between different parts of the body.[30]
In vertebrates it consists of two main parts: the Central nervous System (CNS) that consists of the brain and spinal cord and the Peripheral Nervous System (PNS) that consists mainly of nerves that connect the CNS to every other part of the body.
The nerves that transmit data from the body to the brain are called sensory nerves. On the other hand, the motor nerves work the other way around. The Spinal nerves can work both receive and send data from the body to the brain, so they are called mixed nerves.
Neurons send signals to other cells through thin fibers called axons that cause chemicals known as neurotransmitters to be release at junctions called synapses [31]. Then the synapse gives a command to the cell. This entire communication process usually only takes a fraction of a millisecond.
Sensory nerves react to physical stimulus and send feedback to the CNS and the motor nerves transmit signals to active the muscles or glands. [30]

Spinal Cord

One of the most important part of the nervous system is the spinal cord.
The spinal cord is a long structure with a cylindrical shape that begins at the end of the brain stem and continues down almost to the bottom of the spine (spinal column). It occupies 2/3 of the vertebral canal. [32]
It consists of nerves that carry data between the brain and the rest of the body (as said in Section 1.2.3).
The spinal cord is surrounded by three meninges (layers if tissue): [33] [34]

- dura mater
- arachnoid mater
- pia mater

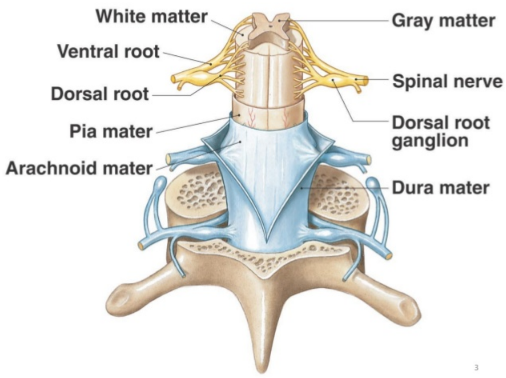

Figure 1.7: Spinal Meninges [35]

The spinal cord and meninges are contained in the spinal canal, which runs through the center of the spine. [36] In adults, the spine is composed of 26 individual back bones (vertebrae) that protects the spinal cord. The vertebrae are separated by disks made of cartilage which acts as cushions, reducing the forces generated by body movements.

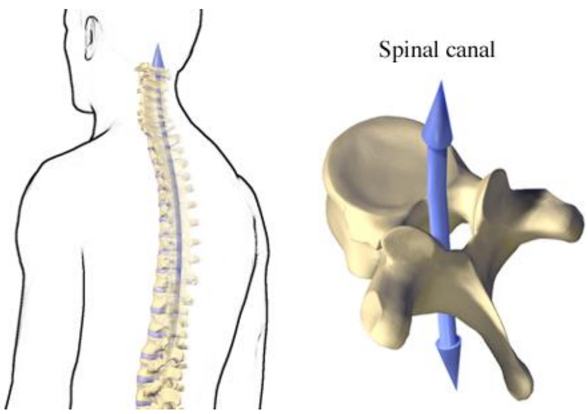

Figure 1.8: Spinal Canal [37]

Emerging from the spinal cord between the vertebrae are 31 pairs of spinal nerves: [38] [33]

- 8 cervical (C)
- 12 thoracic (T)
- 5 lumbar (L)
- 5 sacral (S)
- 1 coccygeal (Co) - mainly vestigial

Each nerve emerges in two short branches (roots):

- One at the front (motor or anterior/ventral root) of the spinal cord
- One at the back (sensory or posterior/dorsal root) of the spinal cord

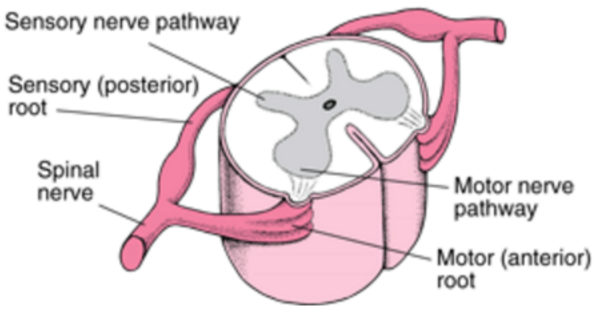

Figure 1.9: Spinal Cord Structure [36]

Just like the brain, the spinal cord consists of white and gray matter.
The butterfly-shaped center of the cord consists of gray matter. The front wings(called horns) contain motor nerve cells, which transmit information from the brain or spinal cord to muscles, stimulating movement. The back horns contain sensory nerve cells, which transmit sensory information from other parts of the body through the spinal cord to the brain. The surrounding white matter contains columns of nerve fibers that carry sensory information to the brain from the rest of the body (ascending tracts) and columns that carry impulses from the brain to the muscles (descending tracts). [36]

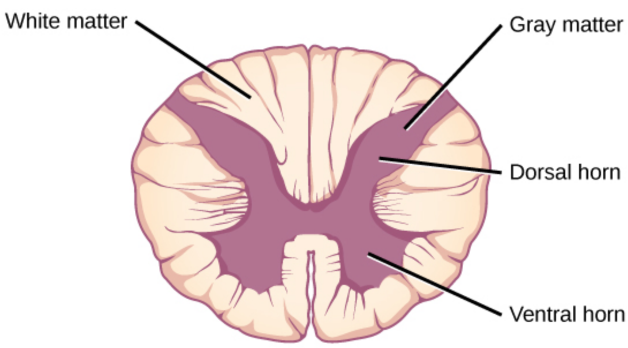

Figure 1.10: Spinal Cord [39]

Spinal Nerve Roots

The spinal nerves consist of the sensory nerve roots (dorsal), which enter the spinal cord at each level, and the motor roots (ventral), which emerge from the cord at each level. [38]
The spinal nerves are named and numbered according to the site of their emergence from the vertebral canal.
C1-7 nerves emerge above their respective vertebrae. C8 emerges between the seventh cervical and first thoracic vertebrae. The remaining nerves emerge below their respective vertebrae.

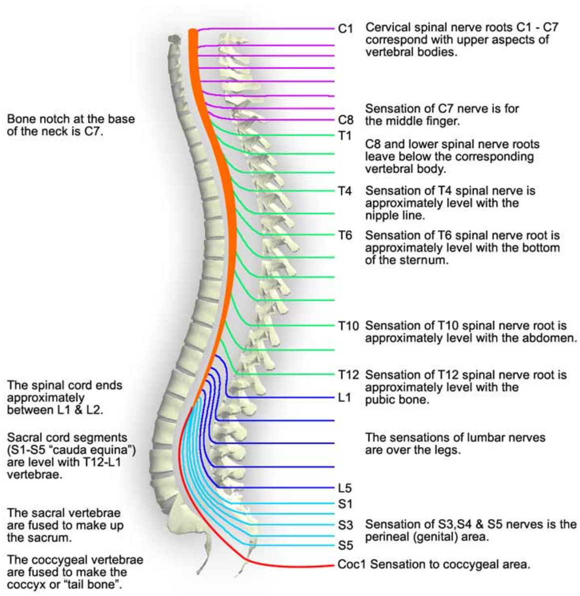

Figure 1.11: Spinal Nerve Root Relation [40]

As it can be seen in Figure 1.11, the dorsal rami of C1-4 are located in the suboccipital region (neck). C1 participates in the innervation of neck muscles. C2 carries sensation from the back of the head and scalp, along with motor innervation to several muscles in the neck. C3-C5 contribute to the formation of the phrenic nerve and innervate the diaphragm. C5-T1 provide motor control for the upper extremities and related muscles. The thoracic cord has 12 segments and provides motor control to the thoracoabdominal musculature. The lumbar and sacral portions of the cord have 5 segments each. L2-S2 provide motor control to lower extremities and related muscles. The cord ends at vertebral levels L1-L2. [38]

1.2.4 Rehabilitation

Physical rehabilitation is the process of restoring and regaining physical strength and function. [41] It is used to return (or give) the maximum of functionality to a person that has an acquired condition (for instance, to help treat a simple ankle sprain or to help a stroke survivor walk, talk and eat again). In rehabilitation, what the doctor tries to do is to restore, in an anatomic way, but more important, give the patient autonomy

and functionality executing daily routines with the maximum normality.
It can be used in orthopedic cases, musculoskeletal, neurological, cardiorespiratory, palliative and so on. It is applied since birth till death.

Figure 1.12: Rehabilitation [42]

Sometimes only one root of the spinal cord gets ruptured and depending on which part a person can feel different symptoms. For instance, if the dorsal root gets a rupture, a person can still be able to feel pain but not know how their foot is positioned or feel vibration.
Tabes dorsalis, also known as *syphilitic myelopathy*, is a genetic disease that does exactly that. [43]
Nowadays, the tests that are done to check the vibratory sensibility of the patient are done using a tuning fork (also known as a diapason).
A tuning fork is a steel or magnesium-alloy device that produces harmonic vibration when its two prongs are struck. [44]
Usually, in a diagnose test using the tuning fork, the doctor asks the patient to close their eyes and then proceeds to lean the diapason in the patient body (with the patient having to ignore the sense of touch and cold of the sudden contact). The patient is then requested to tell the doctor when the sensation is gone.

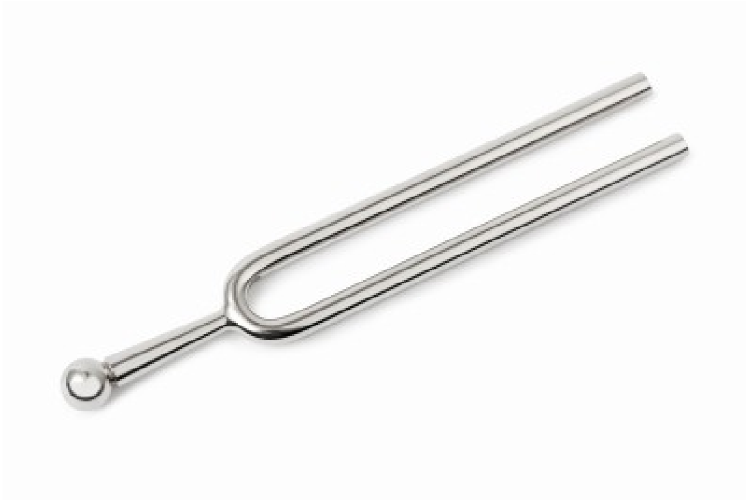

Figure 1.13: Tuning Fork [45]

1.3 Thesis Guide

The stages of this work are presented in the following chapters, organized as follows:

- Chapter 1 briefly explained the context and objectives of the current project. A state of the art review on the principles of haptic, robotic teleoperation, nervous system and rehabilitation were also exposed.
- Chapter 2 consists on the explanation of the proposed solution and the materials used to achieve it.
- Chapter 3 explains the development of the application both in the hardware and software part.
- Chapter 4 presents the experiments undertaken to test and validate the methodologies described in this project.
- Chapter 5 discusses the conclusions of this project and also presents some proposals for future works.