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Master Thesis:

## Integration of visual feedback and virtual fixtures in a unity-based da Vinci robot simulator: a usability study for safer robotic surgery

Tutor:

Alessandro Rizzo

Tutor:

Elena de Momi

Co-tutor:

Ziyang Chen

Graduate Student:

Filippo Maria Liardo

# ABSTRACT

In the past two decades, robotic assisted minimally invasive surgery (RAMIS) has made incredible strides, enabling less invasive surgical procedures, reducing patient trauma, and improving practitioner comfort. However, RAMIS techniques need a physical separation between the surgeon and the operating table, which limits the practitioner's ability to see the surgical scene because they rely solely on the endoscopic camera's visual feedback. Additionally, the surgeon is unable to gauge the amount of force he is applying to tissues and organs without coming into direct contact with the surgical equipment, which could potentially harm sensitive structures. In order to enhance the safety of the method and the surgeon's ability to perceive the anatomical site in three dimensions, virtual fixtures are control techniques that permit the practitioner to obtain force feedback whenever the surgical tools are in close proximity to pre-defined anatomical structures. In this thesis, a virtual fixtures system for the da Vinci surgical system is created, and there is another type of virtual fixture system that is visual feedback. They consist of a virtual surgical scene and a computation of the shortest distance between the complete instrument's shaft and the anatomy.

The virtual fixtures are based on three different models:

- Force feedback by visco-elastic model force
- Force feedback by a sigmoidal function model force
- Visual Feedback

This project is a simulator that might enhance the surgeon's proficiency with this machine, so it's necessary to create a good virtual environment

for instructing the doctor. The simulator has been proven effective in two critical areas: rendering a perception of the shape of the 3D restricted structure, which is a crucial component in enhancing the surgeon's perspective of the surgical scene and avoiding collisions without impeding the execution of the surgery. The method successfully prevents the tools from colliding with the anatomy by greatly extending the distance between them while maintaining the ability to do the procedure, according to the results.

# ABSTRACT VERSIONE ITALIANA


Negli ultimi due decenni, la chirurgia mininvasiva assistita da robot (RAMIS) ha fatto passi da gigante, consentendo procedure chirurgiche meno invasive, riducendo il trauma del paziente e migliorando il comfort dell'operatore. Tuttavia, le tecniche RAMIS necessitano di una separazione fisica tra il chirurgo e il tavolo operatorio, che limita la capacità dell'operatore di vedere la scena chirurgica, poiché si affidano esclusivamente al feedback visivo della telecamera endoscopica. Inoltre, il chirurgo non è in grado di valutare la quantità di forza che sta applicando ai tessuti e agli organi senza entrare in contatto diretto con l'attrezzatura chirurgica, che potrebbe potenzialmente danneggiare le strutture sensibili. Per migliorare la sicurezza del metodo e la capacità del chirurgo di percepire il sito anatomico in tre dimensioni, i dispositivi virtuali sono tecniche di controllo che consentono al medico di ottenere un feedback della forza ogni volta che gli strumenti chirurgici si trovano in prossimità di strutture anatomiche predefinite. In questa tesi, viene creato un sistema di dispositivi virtuali per il sistema chirurgico da Vinci, ed esiste un altro tipo di sistema di dispositivi virtuali che è il feedback visivo. Il sistema consiste in una scena chirurgica virtuale e nel calcolo della distanza più breve tra l'asta dello strumento completo e l'anatomia.

I dispositivi virtuali si basano su tre diversi modelli:

- Feedback della forza mediante un modello di forza visco-elastico

- Feedback di forza mediante un modello di forza a funzione sigmoidale
- Feedback visivo

Questo progetto è un simulatore che potrebbe migliorare la competenza del chirurgo con questa macchina; quindi, è necessario creare un buon ambiente virtuale per istruire il medico. Il simulatore si è dimostrato efficace in due aree critiche: rendere una percezione della forma della struttura ristretta 3D, che è una componente cruciale per migliorare la prospettiva del chirurgo della scena chirurgica ed evitare le collisioni senza ostacolare l'esecuzione dell'intervento. Secondo i risultati, il metodo riesce a evitare che gli strumenti entrino in collisione con l'anatomia estendendo notevolmente la distanza tra di essi, pur mantenendo la possibilità di eseguire l'intervento.

# Contents

# 1 | INTRODUCTION

## 1.1 MOTIVATION

Robotic-aided minimally invasive surgery (RAMIS) has undergone significant improvement over the past 20 years, offering both the patient and the doctor a number of benefits. Robotic-assisted operations actually guarantee less harm to the patient's tissues and organs, less discomfort and scarring, as well as shorter hospital stays, when compared to traditional open surgery. The implementation of features like motion scaling and tremor filtering, which can enhance the surgeon's performance, is also advantageous. Even while RAMIS has several benefits over open surgery for both the patient and the surgeon, there are also certain disadvantages. First off, during minimally invasive operations, the surgeon only sees the anatomical site through the endoscopic camera's visuals. The endoscope structure requires the two cameras to be close together, which can distort the feeling of depth even if in some systems using a stereoscopic camera can extract a three-dimensional perception of the view. Additionally, the presence of smoke and blood at the surgical site can impair the visual feedback, further reducing the surgeon's vision. The practitioner has no feedback on the force he is applying to anatomical structures, which is a second disadvantage that is somewhat related to the first. The endoscope structure requires the two cameras to be close together, which can distort the feeling of depth even if in some systems using a stereoscopic camera can extract a three-dimensional perception of the view. Additionally, the presence of smoke and blood at the surgical site can impair the visual feedback, further reducing the surgeon's vision. The practitioner has no feedback on the force he is applying to anatomical structures, which is a second disadvantage that is slightly related to the first. One drawback of the lack of haptic feedback is that the surgeon is compelled to examine visual signals (such as tissue deformation) in order to gauge the applied force, which might slow down the procedure's workflow. On the other hand, it can compromise the safety of the treatment because the device might run into and pierce delicate anatomical tissues. Thus, the addition of haptic interfaces to surgical robots has the potential to enhance both the practitioner's RAMIS performance and the safety of the process. However, because of the instrument design and safety considerations, adding force sensors to surgical instruments might be difficult. A virtual fixture control technique can be used to implement a realistic, software-generated force as a potential substitute. The primary focus of this thesis project is on teaching how to use the Da Vinci Robot, how to operate with a virtual fixture effect from force feedback, and how to have a perception of how to see the environment from a master machine, which addresses another issue that has not arisen from RAMIS: preparing the doctor to use these types of devices that at first may be challenging to use. Virtual fixtures (VF) are cooperative control techniques that limit the motion of the robotic device uniaxially. To avoid the robotic instruments clashing with delicate anatomical components in the context of collaborative surgical robotics, VF are being studied. The practitioner will feel resistance when travelling in a risky direction if a force is applied to the master robotic handlers when the instruments are close to the anatomy. Virtual fixtures function by simulating the reality of the operating room and using that representation to measure the distance between the instrument and the anatomy. A force is applied to the practitioner when the distance is below a predetermined threshold. The representation of the relationship between the surgical tools and the anatomy in the virtual fixture's design is extremely important. The representation of robotic tools is typically restricted to a single point, which corresponds to the tip of the tool. Although the tip interacts with the anatomy the majority of the time, it is constantly in the surgeon's field of vision, decreasing the likelihood of unexpected accidents. Instead, the shaft of the instrument, particularly for the lengthy ones utilised in RAMIS, accidentally exits the frame of view of the camera.

## 1.2 AIM OF WORK

The integration of a virtual fixture system on the da Vinci robot is suggested in this thesis work with the ultimate goal of increasing the safety of RAMIS procedures and the practitioner's understanding of the anatomical site. As has already been mentioned, the goal of this master's thesis is to enhance the surgeon's capacity to employ these robots. These innovations will shape medical practice in the future, and this initiative should make it easier for surgeons to operate on patients with robots. In this experimental thesis, the virtual fixture system is used in a kidney environment, and it will be crucial to compare the differences between an operation with and without a virtual fixture system. The implementation of a virtual fixture system has been done to reduce the potential damage in the neighborhood of the possible sites where the surgeon is working.

# 2 | STATE OF THE ART

In this chapter there will be a summary of the history of robotic surgery; that is, how it has evolved over time up to the present day; then we will discuss the concept of virtual fixtures and then go into more and more specifics until we focus on the concepts preponderant for this thesis project.

## 2.1 SURGICAL ROBOT

Robotic surgery is a term used to describe certain surgical techniques. Robot-assisted assisted surgery was created in an effort to get around the drawbacks of existing minimally invasive surgical techniques and to improve the skills of surgeons practicing open surgery. In minimally invasive robotic-assisted surgery, the surgeon administers the tools of the robot in two ways: the first would be direct telemanipulation, and the other is computer-controlled manipulation; thanks to them, there is no need to move the rods manually. A tele-manipulator is really a remotely operator that gives the surgeon the ability to carry out the typical movements needed for the procedure. To carry out the actual surgery, the robotic arms use end-effectors and manipulators.

### 2.1.1 BRIEF HISTORY OF SURGICAL ROBOTICS

Any machine that can be programmed by a computer and is capable of performing a complex set of tasks automatically is referred to as a robot. An external control device or an internal control could be used to steer a robot. The term *robotics* was first introduced by Isaac Asimov in 1942 in the short story "Runaround", where he also published the three laws of robotics:

1. "A robot may not injure a human being or, through inaction, allow a human being to come to harm."
2. "A robot must obey any orders given to it by human beings, except where such orders would conflict with the First Law."
3. "A robot must protect its own existence as long as such protection does not conflict with the First or Second Law." [1]

Asimov's zero rule was added to them in 1985. The definition of a robot as an industrial product created by skilled engineers or technicians has changed since the creation of the robot rules:

0. "a robot may not injure humanity, or, through inaction, allow humanity to come to harm." [1]

When General Motors created the Unimate in 1958 to help with the production of automobiles, science fiction became reality. Since that time, a broad range of businesses have used robots, including the military, marine environment and aerospace research, and search and rescue activities. Robotics' overall goal is to replicate or enhance human function or fill roles that are too dangerous for direct human labor [2]. The surgical field would have been a field that would have exploited the evolution of technology so much that, after a series of years, people began to think about how robots could intervene in the surgical field. The first robots to be utilized in real-time surgical procedures were active robotic systems, which operate on pre-programmed data and computer-generated algorithms. The first surgical use of industrial robotic technology was disclosed in 1985 when a stereotactic brain biopsy was carried out using a modified industrial robotic arm. The ROBODOC (Integrated Surgical Systems), which was the first active system to operate exclusively for surgical operations, was first launched in 1992 for use in hip replacement surgery. It is made up of an ORTHODOC computer workstation for preoperative planning and the ROBODOC surgical assistant, which features a five-axis robotic arm with a high-speed milling device (end effector)


*Figure 2.1: ROBODOC on the right side of figure while the ORTHODOC image on the left side*

attached to the tip of the arm via a force torque sensor (see Figure 2.1). By evaluating the fit and fill of various implants, ORTHODOC 3-dimensional (3D) preoperative planning, which is carried out based on computed tomography (CT) imaging data, enables surgeons to choose the ideal design and size of the femoral component for each patient. Data, including the optimal plan, is sent to ROBODOC, which, following firm attachment of the bone to the ROBODOC, registration of the femur, and calibration of the milling bar, mills the bone cavity to the same dimension as the matching rasp [3]. A few years later, ROBODOC also received FDA clearance, making it the first robotic device. More than 28,000 operations all around the world have used this instrument [4]. Another important device in the history of surgical robotics was the AESOP (automated endoscopic system for optimal operation), which was produced by the collaboration between the Computer Motion industry and NASA SBIR (small business innovation research). The AESOP robotic surgery system (figure 2.2) is made up of two pieces from a technological perspective: a robotic arm that carries an endoscope attached to the operating table's instrument rail and a computer system with a surgeon-specific (speaker-dependent) voice control system.

*Figure 2.2: AESOP robotic surgical system*

The implementation of the commands communicated by the headset microphone worn by the surgeon during the surgery is increased thanks to this modeling technique, which necessitates the voice being recorded beforehand. Such a device is designed to enhance picture stability, prevent unnecessary endoscope motions that might smear the lens, and lower the number of medical staff members needed in the operating room [5]. AESOP was approved by the FDA in 1994. After that, there have been some updates to this machine until the production of ZRSS (ZEUS Robotic Surgical System), which was approved by the FDA in 2001 (see figure 2.3).


*Figure 2.3: ZEUS Robotic surgical system*

The surgeon uses the Zeus while seated at a workstation and uses polarised goggles to observe the surgical procedure in three dimensions. The Zeus system is no longer marketed because Intuitive Surgical purchased Computer Motion Inc. in 2003. The first telepresence surgery was performed in 2001 using the Zeus surgical equipment. The first transatlantic medical procedure, a laparoscopic cholecystectomy, was carried out on a patient in Strasbourg, France by a surgeon sitting at a console 3,800 miles away in New York, realizing the military's dream of telepresence surgery [5]. Nowadays, the most used surgical robot in medical establishments is the Da Vinci, by Intuitive Surgical, which has taken the place of ZEUS as the company's main product. In hospitals and other institutions all across the world, there are more than 5000 da Vinci surgical systems in use [according to 2020 data [6]. This robot (figure 2.4) is composed of two effective positions: the first is the "work area," where there are three arms that comprise the surgical instrument and another arm to see what is happening. The second position is called the "Master position," where the surgeon is seated while performing the surgical operation and commands the four robot arms.


*Figure 2.4: the Da Vinci surgical system*

The master console presents a foot pedal that permits changing the robot arm position with the camera to see the worktable, and the images come from an endoscope stereo-camera and a High-Resolution Stereo Camera (HRSV). Surgeons may now carry out various surgical procedures with more accuracy, reproducibility, and delicacy thanks to robotic devices like this one. However, performing the procedures with a high degree of dexterity and visualization needs lengthy approaches and techniques and time-consuming training, which mandates substantial instruction [7]. The da Vinci Surgical System is frequently utilized in gynecology operations, cardiac replacement, and prostate extraction operations. These three surgical robots mentioned briefly explain the evolution of robotics in the medical field, and the innumerable success of the Da Vinci does not constrain the presence of other various types of surgical robots in the current market, even for purposes other than itself.

### 2.1.2 CLASSIFICATION OF SURGICAL ROBOT

Typically, three types of robotic surgery exist:

1. Shared controlled
2. Tele-surgical
3. Supervisory-controlled

The most automatic of the three approaches is the supervisory controlled one. A supervisory-controlled system used in orthopedic procedures is the ROBODOC from Integrated Surgical Systems Inc. The ROBODOC autonomously mills the bone to the precise size needed for the orthopedic implant once the surgeon places it in the proper location within the patient. The tele-surgical technique enables the surgical machine to be remotely controlled by a real surgeon, or teleoperated. The da Vinci Surgical System makes use of telesurgery. The term "shared-controlled approach" describes a technique in which the robot is not simply motion teleoperated but also has the option to determine whether to oppose the surgeons' intended movement if it would be ineffective [8].

## 2.2 HAPTIC IN ROBOTIC-ASSISTED SURGERY

It is currently difficult to equip existing surgical robotic systems with tactile feedback to carry out minimally invasive surgery (MIS), like laparoscopy. In surgery remotely operated systems, the haptic element is eliminated, which restricts the powers and capacities of surgeons. The surgeon would benefit greatly from the availability of haptics in the following ways: among other things, improved tissue handling, less suture tearing, and a stronger sense of telepresence.

### 2.2.1 THE NEED FOR HAPTIC FEEDBACK

Haptics combines tactile (skin texture and fine detail) and visual-spatial (form and shape of muscles, tissues, and joints) perception. It also combines several physical factors, such as strength, distributed strain, heat, and motion. The following are the immediate advantages of detecting contact forces at the surgical end-effector:

1. enhanced characterization and manipulation of organic tissue
2. analysis of the skeletal system
3. decrease in suture breakage
4. An improvement in how aided robotic surgery feels overall.

Additionally essential to reducing the learning curve for trainee surgeons in MIRS is haptic feedback [9]. The relative closeness of the two cameras on the endoscope limits the sensation of dimension, including in systems that offer stereoscopic images, as in the da Vinci system. The fact that liquids and fumes may obstruct the endoscopic camera's pictures and degrade the visual input makes the problem much worse. Due to the surgeon's limited ability to see in three dimensions and the lack of feedback on the amount of force being applied to anatomical structures, there may be unnecessary bleeding, instrument collision with sensitive tissues, and procedure lengthening because the surgeon must occasionally pause the maneuver to look for visual cues to improve their perception of the surroundings [23]. The associated telerobotic system's transparency is another name for the teleoperation fidelity of force feedback. This attribute relates to the operator's perception of a distant interaction. In other words, it describes how the reflected force field is deviated by the telerobotic medium and how the distant impedance has reflected the user. The force field will be extremely accurately reflected by the ideal telerobotic system, ensuring high transparency. It has proven difficult to implement a transparent telerobotic system because, to realize transparent interactions, all system and communication network dynamics must be adjusted in the face of uncertainties and noise. This is a complicated need that necessitates thorough research into the structure of telerobotic architectures. Transparency is crucial in the context of telerobotic surgery since poor force reflection can lead to deceptive haptic signals and fatigue for the surgeon, both of which can have unfavorable consequences [21]. The benefits that could be there with the evolution of this field would be enormous. Even the teaching that novice doctors would receive in the use of surgical robots would receive an important increase because they would have extra support between their teleoperation and the patient.

### 2.2.2 CHALLENGES

Today, how to best compensate for haptic feedback remains a conundrum, and we are still debating which path to take. The first question is at the base of the object, that is, to position the sensor outside the cavity abdominal for example, inducing an indirect force sense or in close contact with the end-effector for a direct force sense. In MIRS, it seems that the best option is to have direct force sensing to avoid the possibility of having further instrumental problems during these surgeries. However, a notable problem is a high cost that a normal robot tip might have, as the strain measurement method and electrical connections must withstand additional autoclavable cycles as well as survive an elevated PH wash. A possible effective solution to this problem is the TELELAP ALF-X surgical system, which utilizes reusable non-wristed laparoscopic devices and is made up of a remote-control unit, manipulator arms, and connecting node. With a remote 3D vision, an eye-tracking camera control system, and an integrated haptic interface, this innovative technology offers a revolutionary method of doing a laparoscopy. Any location on the screen that is being looked at while pushing two buttons on the handles will automatically shift to the center of the screen according to the system's architecture. The surgeon's head movement may zoom in and out on the image, creating the impression that he is doing open surgery. Animal models used in experiments demonstrated the viability of this novel method even during challenging laparoscopic surgeries [22]. Another important haptics development was created by Mako Surgical (bought by Stryker): the "Mako" robotic system, which works in the prosthetics industry and is made up of a robotic arm, a vision module, and a guiding module. Without getting into the specifics of the device, it uses a technology called AccuStop, based on color changes on the screen that the doctor sees, auditory beeps, and tactile vibrations, to stop cutting and perforation guides in the intramedullary canal, which were crucial during manual orthopedic operations [24]. Despite the high benefits that could be found with the implementation of haptic feedback in minimally invasive surgery, it seems that many manufacturers prefer not to use it for various medical devices as they consider research and excessive expenditure for the company budget.

## 2.3 VIRTUAL FIXTURES

Therefore, virtual fixtures are one of the main topics of this thesis, and therefore, an introduction will be made on how I was introduced to the world of robotics and then go into more and more specifics on the various differences between the existing virtual fixtures and those that will be exploited for this project.

### 2.3.1 THE CONCEPT OF VIRTUAL FIXTURES

Louis Rosenberg was the first to develop virtual fixtures in 1992 at USAF Armstrong Labs. According to their definition, virtual fixtures (VF) are "collaborative control techniques that may be employed to enhance or support human manipulation activities by anisotropically controlling motion [9]". As reflected sensory data from a distant environment is combined with abstract sensory information, this is how virtual fixtures are defined. Virtual fixtures are fully independent of any information from the remote site, even if they are layered on top of the user's impression of the remote environment, as a result, they are unaffected by communication lag and bandwidth restrictions. Virtual fixtures superimposed on top of a remote workspace, such as the ruler guiding the pencil, may reduce the amount of mental processing required to complete the task, reduce the workload on some sensory modalities, and, most importantly, allow precision and performance to exceed naturally human abilities [25]. The implementation of this technique could go to improve the gap due to the lack of feedback between the patient and the robot itself, although it is not a solution that could be precise as a haptic feedback sensor, it could certainly significantly reduce the margins of error of the doctor during surgical operations and would not require a high economic increase for the company. There are two types of virtual fixtures: the first is the "Forbidden region virtual Fixture" (FRVF), which has as its main objective the reduction of the working space, to block the instruments to have dangerous poses and configurations The other type of virtual fixture is the "Guidance" restrictions, known by the acronym HGVF, which means "Haptic Guidance Virtual Fixture", which has the function of indicating the preferred direction to the user, in our case to the doctor, according to the task to be performed. For example, in some studies, this method was used to indicate the best path to carry out a suture with robotic end-effectors. In normal functioning, regional restrictions are less obtrusive to the user than guiding constraints. Yet, the ability to precisely constrain locations is vital in certain applications [9]. Cooperative manipulators and telemanipulators are two examples of human-machine robotic manipulation systems to which virtual fixtures can be applied. In cooperative manipulation, a person directly manipulates an environment using a robotic instrument. In telemanipulation, a master robotic device is controlled by a human operator while a distant slave robot manipulates an environment according to the master's instructions. Typically, impedance or admittance robots can be employed in these systems. Since we are using a master console to command the Da Vinci robot in our project, we will discuss these virtual fixtures in the area of telemanipulation robotic systems:

- It is feasible to build impedance-type FRVFs on telemanipulators by overlaying a penalty-based virtual wall over the existing telemanipulation controller. The virtual wall can be utilized by either the master side or the slave side (or both simultaneously). Both have had the effect of reducing the flow of slaves into forbidden territories. A proxy may also be used to implement admission-type FRVFs. We can regulate slave movement in confined regions of the slave manipulator by altering the dynamic properties of the proxy, which serves a proxy rather than the master directly. When not interacting with the FRVF, the proxy is designed to exactly follow the master. When the master passes the FRVF, we dampen the motion of the proxy [10].

- The GVFs for telemanipulation devices are often developed as impedance-type systems since the master manipulator in such platforms is usually an impedance-type tactile instrument. The slave manipulator, therefore, can be an impedance-type or an admittance-type gadget. Since we don't directly control the system's velocity in some of these settings, we are unable to do admittance control [10].

Another distinction between dynamic and static virtual fixtures is another crucial aspect of virtual fixtures; while dynamic virtual fixtures are based on a working environment of calculation that changes over time, static virtual fixtures are based on a workspace in which there are no changes during operation. In the biomedical area, dynamic virtual devices receive more attention since, in the human body, the effect that different organs get from blood flow, pulse, and breathing includes a change in the working space per second. For this thesis project, the environment represents a kidney, which will remain the same for the duration of the task, so we included a static Forbidden Region Virtual Fixture because of the last thing that they said before.

### 2.3.2 CONSTRAINT DEFINITION

The first thing that should be addressed while conducting studies, tests, and research in the context of the Forbidden Region Virtual Fixture is to determine which zone is regarded as a "workspace" and which is considered a "forbidden" area. This distinction forms the basis of this strategy. The task region could basically be an organ, which has an area on which to operate and on which to perform the various surgical functions, while in the outline of it, one should pay attention because, for example, there are veins that when touched with surgical instruments could cause hemorrhages. Hence the need to divide the areas on which to have virtual fixtures that would have the task of getting me out of a dangerous area, into other zones where the surgeon does not receive any feedback to go out because their instruments are in a "safe-region". In other cases, before evaluating the safe region and the forbidden, it is important to identify where the tools of the robots are located. There are many studies that allow us to observe how to make the most of FRVF, such as being a starting point for our thesis project. In this research [11], first, the evaluation of the positions of the surgical instruments is the most important, and it uses laparoscopic images to do it. The model's output is a picture in which each pixel represents the chance that it is part of the instrument or the background. The binary segmentation is then achieved, where all instrument pixel values are set to 255 and all background pixel values to 0. Re-projecting the tool tip's kinematic location onto the picture plane and creating a rectangle centered on the projected point narrows the search area range in order to identify the tooltip on the image plane. Then, a triangulation approach with direct linear transform is used to rebuild the 3D position of the PSM2 tip as it is expressed in the camera frame. After defining the position of the end-effectors with the use of laparoscopic images, they use the Forbidden Region Virtual Fixtures to avoid collisions with the end effectors of the robotic arms of the Da Vinci surgical robot, that is, PSM1 and PSM2, which we will see specifically in subsequent chapters. The solution lies in the fact that the FRVF has been imposed on an end-effector, which would be the PSM2, and the virtual fixtures are nothing more than a swept surface along the axis of the PSM2. The forbidden region is defined by a cylinder, which would be the surface mentioned above, and the effectiveness of this function has been evaluated by rotating the PSM1 around the PSM2 with a radius equal to the cylinder which will separate the safe zone from the worried zone [11]. Another important research to mention is [12], where they do 3D reconstruction using the difference between the two endoscope pictures, producing a 3D point cloud that is defined in relation to the coordinate system of the camera. The surgeon used a graphic tablet attached to the system to manually identify a 2D "safety area" before fitting it onto a 3D point cloud to choose the volumetric part that corresponded to the structure that was to be safeguarded. This technique, which was used in a similar fashion in [13], enables the localization of the structure that must be safeguarded at a low cost and with efficiency, as well as the creation of a 3D model of the structure in the form of a point cloud. Other studies have also been conducted that rely on the acquisition of intraoperative CT or MRI images for the creation of meshes that could give a representation of the anatomical area on which the operation will have to be performed. To give an example, in this work [14], the anatomical area, which derives from a preoperative CT scan, has been divided into various triangles, fundamental for the creation of the polygon mesh, of which the applied concept is a method based on local convexity and concavity of anatomical surfaces must be used to dynamically activate and deactivate restrictions. Fig. 2.5a shows how a locally concave surface generates a convex set of linear constraints. All triangles can be safely treated as plane restrictions (Fig.2.5b). A locally convex surface (Fig.2.5c) results in a set of linear constraints that are not convex. If all triangles are arbitrarily included as flat boundaries, many suitable areas will be excluded (Fig.2.5d), where the blue represents the patient's anatomy and from these simple images the reason for the exclusion of some areas.

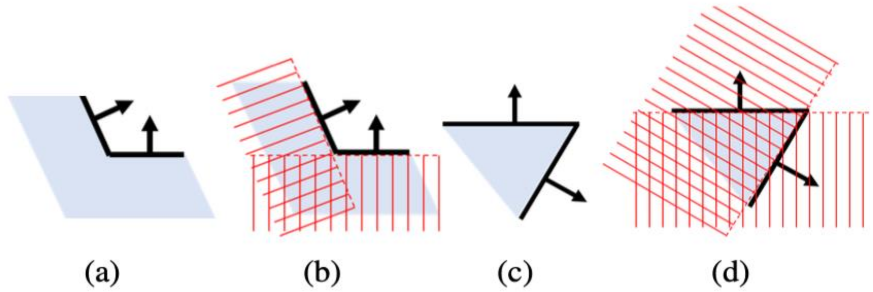


*Figure 2.5: illustration of (a-b) a locally concave surface, and (c-d) a locally convex surface*

The triangular subdivision of it meshes will be very important for this thesis study, which will have as one of the main concepts the triangular subdivision of its meshes used and useful for the algorithmic calculations of the Virtual Fixtures. The previous paper presents particularities that were essential for this work, but another paper that proved to be very useful is the publication [15], which as summarised in some circumstances, is not the end effector, as the tip or the final portion of the medical instrument may be the part closest to the patient, but one may encounter moments during the operation where another point of the instrument is the most important part. In the latter work mentioned, the tools are divided into four segments and are also divided into other segments, and this approach is to evaluate more points in the tools. The final effectors have a lot of points that represent them and after which the distance between the possible anatomy of the patient and the points of the instruments is calculated. The point is the shortest distance that presents the parts that are closest to the patient. All the notions and methods listed have been useful for the achievement of this thesis or have given rise to various ideas for its achievement.

### 2.3.3 CONSTRAINT EVALUATION

The most important part after evaluating the work areas or to pay attention to is undoubtedly the possible application of force, but often another consideration is to narrow the work field even more, in order to reduce possible algorithmic samplings or the date on which you are working to then define even more the region of interest and subsequently observe whether the application of virtual fixtures is necessary or not. In one of the studies mentioned above, that is the [14] after having defined the "polygon mesh", to actually identify the current workspace, they did this: a volume of movement around the current position of the robot has been implemented, based on the maximum environment that the end-effector could cover, and, as a volume, a sphere has been defined, which in turn, as a radius, will have the maximum possible distance that the tool can travel. From this derives the interaction with the "polygon-mesh", which will not be taken into total consideration, but the workspace will be defined by the interaction between the triangles of the mesh and the sphere that covers the tool. We can see from this work how the forbidden or safe area is defined step by step by the movement of the tool. The most important part after the delimitation of the actual current workspace is the definition of the closest point to the object with respect to our tool. We often rely on so much data that various solutions are sought to do the job. To such an extent, a method has been presented in [16], where with a covariance tree data structure, we search for the closest position of the tool from the taskspace. An alternative to a k-dimensional binary tree is a covariance tree (k-D tree), where along the main coordinate axes, the conventional k-D tree structure divides space recursively. Each sub-space in their covariance tree is specified in a local coordinate frame along the orthogonal eigenvectors that are centred at the centre of mass of the point set. Covariance trees have the benefit of having bounding boxes that are often significantly narrower than those found in traditional k-D trees and that frequently line with surfaces, resulting in a more effective search. The tree will be composed after various samples have been given, which will be used to calculate the various moments and the centroid for each group and from which it will then be possible to present the final boxes on which the possible "closest point" will be placed, as well as the most in contact with the end-effector of the robotic arm or any other part of the arm that will be closest to it. This method that has been mentioned is useful for making the various algorithmic calculations simpler since it simplifies the various data present since often there could be values that would cause noise and slowness during the operation. Other methods used in the papers already nominated present typologies of methods like those mentioned, such as the study [15] where the tool was divided into various segments and to identify between the two tools which one presented the segment with the point closest to the patient, they used a method called proximity queries, which was used in [17] and it will be very useful for this project because is strictly dependent on how constraint has been formulated. Subsequently, having identified the segment of the end-effector closest to the patient, remembering that as end-effectors, since we are talking about operations and experiments on the Da Vinci, we refer to PSM1 or PSM2, a k-d tree is used that allows to have more quickly the minimum distance between the tool, that is, from the closest point, and the patient. At the end of this paragraph, we want to mention how the "closest point" has been defined, which derives from the study [14] and is in turn important since it addresses this topic through triangular meshes, which are present within this work of thesis, which is based on the Unity3d program, which contains every object inside it as triangular meshes. This method, which has been mentioned in the [14] paper, is useful for making the various algorithmic calculations simpler due to the fact that it condenses the variety of data provided, since some values may frequently result in noise and sluggish performance. Starting from the fact that, thanks to the volume of movement, it has been defined which triangles to consider calculating the minimum distance between the patient's anatomy and the final instrument, and for the selected triangles, we will work as follows: The plane of the triangle is initially projected at the point of the tip of the tool as it is possible to se in figure 2.7.

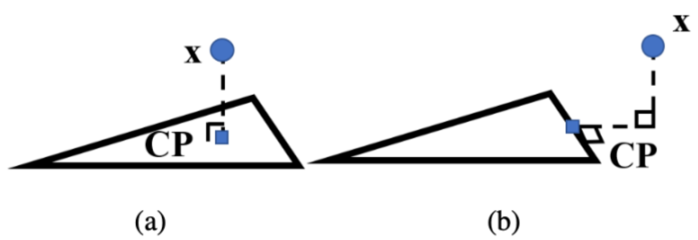


*Figure 2.7: possibile relationship between the point of the tool and triangle of a mesh*

The closest point has been determined if the projection falls inside the triangle. Otherwise, the edges of the triangle are searched for the point. Inside the [14] paper there are also various other conditions, more specifically for the identification of the closest point and to which triangle it belongs. Nevertheless, having done this, as can be assumed, if the point is inside a favorable zone, the tool will be able to move favorably, otherwise, the virtual fixtures will come into action. This project will present a constraint evaluation that will be similar to some parts that have been mentioned but with an implementation of multiple virtual fixtures.

### 2.3.4 CONSTRAINT ENFORCEMENT

The preceding paragraphs have been useful to understanding from the literature how the various work areas are defined, how the safe and forbidden areas are divided, and also with which methods the possible data are reduced, which often could be superfluous, in order to have the execution of a more precise algorithm and with the least possible delay. Now is the time to present how to apply the constraint of the virtual fixtures, that is, the mathematical calculation that arises when you are inside the red zone and the concept associated with it. In the topics that will be cited, the application of a proportional force to a distance will present a different interpretation, but the main concept will be that of compensation between the position in which the tool should be, outside the forbidden region, and the position in which it is currently located, within it, but in turn, different types of forces could be used, and therefore various methods, which will be named, were important for this thesis since, as mentioned in the abstract, the application of constraints will be of various kinds. An important paper to mention, which is based on a force directly proportional to the distance, is [18], where a viscoelastic force is applied, which will subsequently be used in our project, comprised of placing a virtual damped spring between the robotic tool and the limited volume allow the constraint enforcement approach to be implemented. The enforcing function of viscoelasticity is

$$f_p = k_p(p_d - p_c) + k_d(\dot{p_d} - \dot{p}_c)$$

where $f_p$ denotes the force of constraint $p_d$ and $p_c$ stand for the present and intended tool positions, respectively, whereas vector , $k_p$ and $k_c$ are the proportional and derivative gains. If the robotic tool violates the constraint, the desired tool position is set to be the closest point on the surface of the bound region, creating the virtual linkage that ultimately generates the repulsive force. If the robotic tool is within the constrained region, the desired position coincides with the actual one and the force is zero. Various studies and research use viscoelastic forces as an applied force for their virtual fixtures. Also, in the study [19], it is applied with the only difference that it is applied in a guidance virtual fixture (GVF) but it is important to mention it because the constraint enforcement is inserted within an impedance dynamics control, with the corresponding equations, that will be subsequently presented in the next chapter where the methods used will be explained. Another very important concept for the subsequent application of a virtual fixture force is the potential field, which will not be presented in detail but is essentially a scalar field depending exclusively on the position and not on the direction. The next paper that will be cited presents the concept of artificial field since it will be the basis of the evaluation on which the value to which the force will be applied will then depend. Figure 2.8 shows how a potential field was used in the study [20] to identify the heart, which was the object of study.

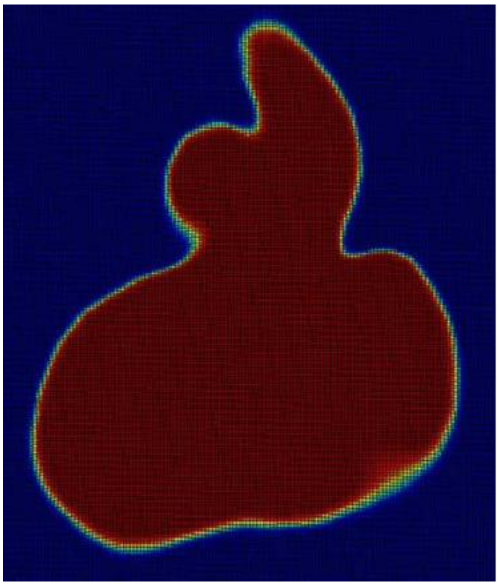

*Figure 2.8: potential field of the entire volume that was selected for the [20]*

However, the focus of this study is on the strength applied when the end-effector was inside the forbidden region, which is a sigmoid force. The sigmoid force that was used is:

$$f = \frac{1}{1 + e^{-\gamma s}}$$

Within the function, there are two variables; the *s* has been introduced as distance indices between the tool and the potential field on which one is working, while the $\gamma$ is a preponderant factor within the sigmoidal functions since, thanks to it, the curve is corrected according to what you want to obtain or what is functional for the current purpose (in the figure [] various examples of how the functions change as the $\gamma$ changes). In this work, it was demonstrated that if we were at the potential field's boundary, s = 0, all points had a potential equal to 0.5, whereas for an s > 0, that is more and more inside the heart region, the value of the internal points approached the unit. All these values were fundamental to then permenterre a force proportional to them, which was calculated by first passing through a negative gradient of the potential field

$$F_q' = -\frac{\partial f}{\partial d}\frac{\partial d}{\partial q}$$

and then the reflected application

$$F_q = f(q)\,\frac{F_q'}{||F_q'||}$$

that led to the exit of the tool from the red zone. This method will be a further inspiration for our project, which, as mentioned in the introduction, will present a sigmoid function and this work was useful for the implementation of this constraint enforcement but will undergo some changes. After discussing how the concept of "constraint enforcement" has been studied in the case of virtual fixtures, especially the forbidden region virtual fixtures (FRVF), we complete the state of the art, which was useful to have a summary on the evolution of robotic surgery, but especially as per the literature, various documents have been studied on the application of virtual fixtures, which is the basis of the thesis project carried out.

# 3 | MATERIAL AND METHODS

This chapter will explain the devices, software, and various scripts used, which contributed to the creation of this simulator set within a mini-invasive surgery operation with the use of various virtual fixtures to improve the accomplishment of the accomplished task.

## 3.1 THE DA VINCI RESEARCH KIT

The birth of this thesis stems from the ambition to be able to work on the Da Vinci surgical robot, which is the main device within this project, and in fact, a more specific introduction compared to the state of the art is due: The first-generation da Vinci Surgical System's robotic parts were used to create the da Vinci Research Kit (DVRK), a telerobotic surgical research platform offered by Intuitive Surgical. Two patient side manipulators (PSMs), one endoscopic manipulator, and two master tool manipulators (MTMs) make up the platform (see Fig. 3.1).

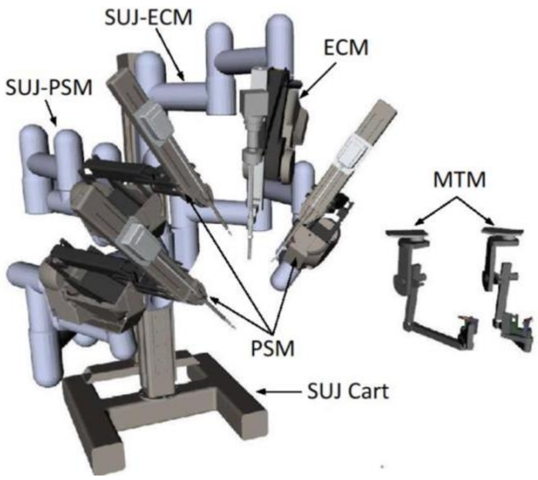


*Figure 3.1: representations of PSMs and MTMs*

A complete ROS-based control of all the DVRK robotic arms is provided through an open controller developed by John Hopkins University. The controller makes it possible to manage the position, speed, and current, which paves the way for the creation and testing of cutting-edge control strategies including impedance control, force control, and bilateral telemanipulation control [26]. In this thesis project, the two patient side manipulators (PSMs) will not be used, which are the end-effectors that would be in contact with the patient himself, because we wanted to design a computer simulator, and therefore the only parts used in the Da Vinci will be the master tool manipulators (MTMs). The patient side and the surgical console, which are shown in figure 3.13, are the two organisational components that make up the hardware portion of the da Vinci system.

*Figure 3.13: surgical room with Da Vinci robot*

The patient cart and the robotic arms are located on the patient side. Three of the arms, known as Patient Side Manipulators (PSMs), may hold a variety of surgical tools, while the fourth arm controls the endoscopic stereo-camera (ECM). Usually located next to the cart, the surgeon's console enables teleoperational control of the PSM, which presents a foot pedal tray, which enables the surgeon to transfer control from the PSM to the endoscope, two joysticks known as the master tool manipulators (MTMs), and High-Resolution Stereo Viewers for visual input make up this device. Both the PSMs and the MTMs are kinematic chains, and the encoder sensors are used to measure the joints' variables. The dVRK's control framework makes use of the sensors' information: the Low-Level Control implements the joint controllers for the da Vinci manipulators, while the Mid Level Control includes the robot's kinematics and has a state machine that controls the robot's states [27]. The Robot Operating System oversees the integration of the dVRK system (ROS). Nodes, which are executable components linked to the ROS network, make up the ROS architecture. By posting and reading content on Topics, nodes may exchange information with one another. For instance, the dVRK system exposes the joint states and poses, as well as those of the end-effectors, on specific subjects that other nodes may access [28].

### 3.1.1 DVRK'S ARM KINEMATICS

The network of joints and links that make up a robotic arm is referred to as the kinematic chain. Each link in the chain has a degree of freedom (DoF) that can either be prismatic, with a degree of freedom for translation, or revolute, with a degree of freedom for rotation. A direct kinematic problem refers to the issue of reconstructing the pose (position and orientation) of the end-effector in relation to the robot's base from the values of the joint's variables. The pose of each robotic link must first be determined in order to solve the direct kinematic issue. Each link's pose may be determined using a reference frame that is solidly attached to it. A homogeneous transform, which is a 4 by 4 matrix with the first three columns representing the rotation matrix defining the orientation of the frame and the last column being the position vector with a "1" appended to it to operate in homogeneous coordinates, is typically used to represent the pose of the frame. Zeros are inserted into the remaining empty spots. The Denavit-Hartenbeg protocol [1] is used in robotics to specify the posture of the link reference frames (RF) in relation to the prior link. The convention requires the geometrical parameters of each link and the value of the joint's variable in order to construct the homogeneous transform describing the posture of each link. The attitude of each connection may be determined in real-time if these factors are known at a specific instant in time. The following chain rule product may be used to determine the posture of the robot's end-effector from the generated homogenous transforms:

$$T_{EE}^{0} = T_1^0 T_2^1 \dots T_i^{i-1} \dots T_n^{n-1} T_{EE}^{n}$$

The patient-side manipulators on the da Vinci are robotic arms with seven actuated revolute joints. These joints have position sensors (potentiometers and encoders) that allow for real-time knowledge of the angles at each joint. Passive Set Up Joints (SUJs), which link each arm to the robot's cart base, allow the arms to be positioned in relation to the patient. The ROS interface of the dVRK system allows users to access in real-time the poses of some reference frames, such as the reference system of the PSMs compared to the reference system of the ECM, but for this project, it will be necessary to have only the position of the right and left manipulator master tools with respect to the reference base.

## 3.2 IMPEDANCE CONTROL

An important method or means that it was useful to apply for the completion of the scripts used regarding the application of forces, is the study of *impedance control*, which was viewed at a theoretical level during the Robotics course, held by Prof. Alessandro Rizzo, and then consolidated at a practical level during the creation of this thesis project. The most important things to know about this robotics concept are:

- imposes a desired dynamic behaviour on how a robot's end-effector interacts with its surroundings.

- A full set of mass-spring-damper equations, or a generalised dynamic impedance, is used to specify the required performance.
- Because there isn't a force error-based control loop, contact forces are only obliquely allocated through the controlling position.

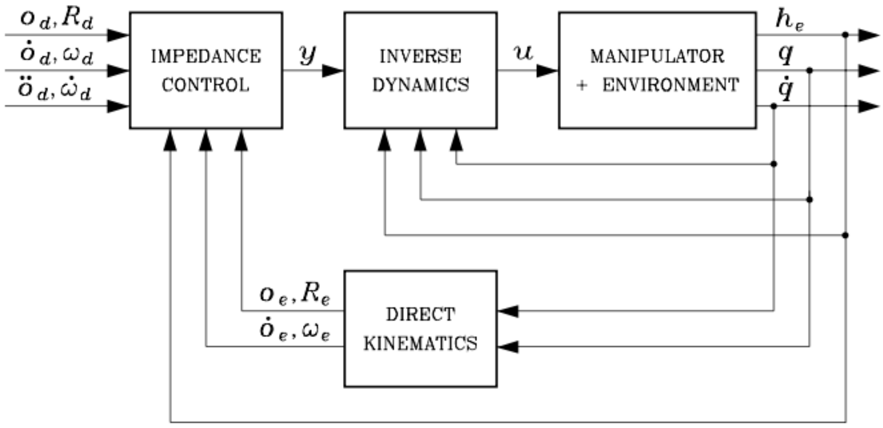


*Figure 3.2: Block scheme of impedance control*

The notions listed are the most useful to summarise the type of control used, and figure 3.2 shows the operations of all this. A thing that seems necessary to include in this summary of the impedance control, also to explain the graph above even better, is the main equation:

$$y = J_A^{-1}(q)M_d^{-1}(M_d\ddot{\tilde{x}}_d + K_D\dot{\tilde{x}} + K_p\tilde{x} - M_d\dot{J}_A(q,\dot{q})\dot{q})$$

A mechanical system that may be utilised to explain the dynamic behaviour along the operational space directions and is characterised by a mass matrix $M_d$, a damping matrix $K_D$, a stiffness matrix $K_p$, a desired direction $x_d$ , and the actual direction $x$. All of these is the source of this impedance control. The introduction of the virtual fixtures, therefore, of the viscoelastic force and the sigmoidal force within the impedance control was made in the part of the figure 3.3 concerning the *inverse dynamics*, and from this, in the final equation of $y$, components concerning these types of forces would appear. The possible impedence dynamics with the corresponding virtual fixtures could be:

$$M\ddot{\tilde{x}} + K_D\ddot{\tilde{x}} + K_p\tilde{x} = f_{vf}$$

Each virtual fixture will have characteristics that will make the results of the above *impedance dynamics* equation different depending on whether we work with the viscoelastic force feedback or the sigmoidal force feedback. Each virtual fixture will present characteristics that will make the results of the impedance dynamics equation above different depending on whether we work with the viscoelastic force feedback or the sigmoidal force feedback. For example, with the use of viscoelastic force on the matrix damping of impedance control $K_D$ , another force-dependent damping will be added $K_{D_{vf}}$, while for the sigmoidal force, the influencing damping will be that of the impedance control only. All this explains how the dynamics of the control could vary according to the type of virtual fixtures that we would like to insert inside.

## 3.3 FRAMEWORKS OF THE PROJECT

The paragraph on explaining the kinematics of the Da Vinci research kit best describes how the project was developed and what information was mainly used. For example, in the first experiments, when working with PSMs and applying virtual fixtures on them, the reference systems on which they were based were necessary for the various computational calculations, but with the idea of the simulator, the only systems of necessary reference were the MTM frame of reference, which refers to the system of the Master with respect to the base, and the reference system of the programme used to create the operating scene, which would be Unity3D, which presents a reference system for left-handers. The Unity3D reference system could present a real problem as from Unity the closest point to the virtual PSM was read and, in turn, through the various scripts, ROS "published" the forces with respect to the desired positions that the PSM had to present if he had been inside a forbidden region. Through commands such as *UnityToRos*, present within the Csharp libraries, it was possible to read the various messages from Unity and bring them back to ROS without any possible conversion, but when it was necessary to publish some position, such as the desired position that the end-effector had to present, from ROS to Unity, various experiments were conducted with the scripts used to find a compromise between the reference system of Unity and that of the Master through various rotations using commands on the Euler angles, present in the C++ libraries, which is the language which is used for writing the codes with which the ideal position of the MTMs were defined (and consequently also the virtual PSMs) and the scripts concerning the forces applied to the MTMs if they were inside the red zones, therefore the virtual fixtures.

## 3.4 SIMULATOR ENVIRONMENT

In the creation of the environment, a comparison with a doctor, Dr Matteo Fontana, was fundamental. He gave some insights on which model would be interesting to create and on what possible tasks could have been worked on for subsequent experiments. The surgery that you will want to resume is a nephrectomy operation or the partial or radical removal of the kidney due to the presence of a tumour on it. Without going into the details of the type of surgical operation, it was discussed how often it was necessary to remove the lymph nodes adjacent to the kidney and surrounding veins during the removal of the tumour in partial nephrectomy, hence the idea of devising as the environment of this thesis project, a part of the urinary system, which will include the kidneys, the aorta, the vena cava, and the lymph nodes around them. We utilized Blender, a free and multi-platform tool for modelling, rigging, animation, video editing, composition, rendering, and texturing of three-dimensional and two-dimensional pictures, to create our work environment. We utilized Blender, a free and open-source 3D creative package, to create the environment in which we operate. You can make 3D visualizations with Blender, including VFX shots, 3D animations, and still photos. Also possible is video editing. Small studios and individuals may profit from its unified pipeline and responsive development approach, making it a good choice for them. Figure 3.3 shows the final result of our model, presenting as a background the image used to create the model itself.

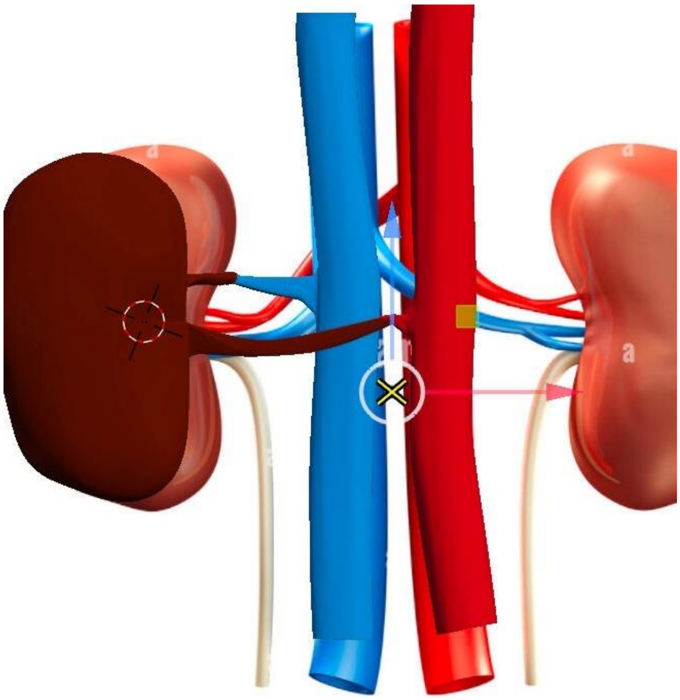

*Figure 3.3: Kidney, Aorta and Cava veins created by Blender*

The renal system created is a fairly simple system, with no particular peculiarities. Indeed, in figure 3.5 it can be seen that the model actually used during the user studies is less linear because it was necessary to reduce the number of triangles making up the mesh of the kidneys, of the aorta and the quarry, since during the algorithmic calculations of the project, the high number of them caused an overload of the system and for this the reduction of the triangles that made up our "polygon mesh", but later on we will better explain the concept of the use of the triangles that make up the system.

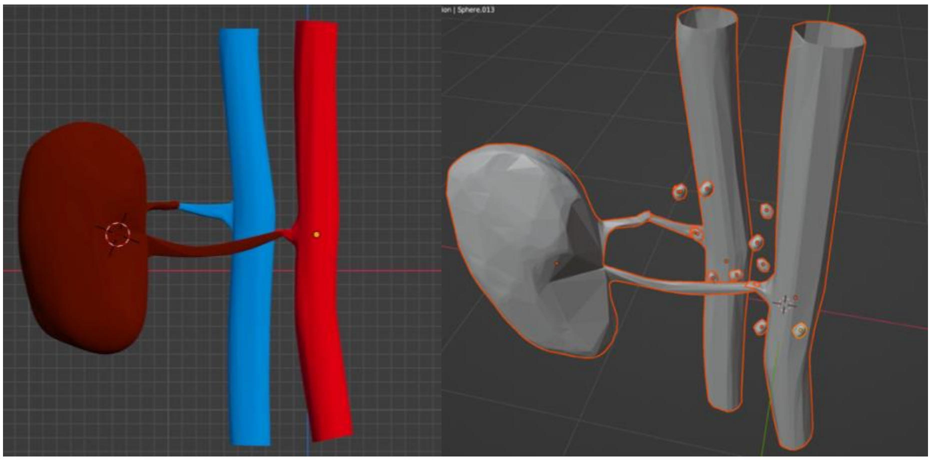

*FIGURE 3.5: represents on the left the final blender model and on the right the used model during the tasks*

## 3.5 CONSTRAINT DISCUSSION

What we will discuss later is how the concepts introduced in the previous chapter about constraint definition, evaluation, and enforcement on the virtual fixtures applied to this work were used. The following paragraphs will go into the details of how the force was applied to the MTMs, also mentioning the scripts used for the achievement of the final objective.

### 3.5.1 CONSTRAINT DEFINITION

In the chapter on the state of the art, the main concepts of virtual fixtures have been dealt with, along with the corresponding steps that any group of researchers or scientists carries out for this specific application. In this thesis work, which has as its main basis the concept of the Forbidden Region Virtual Fixtures, the evaluation of the region on which one does not want to work or rather where the doctor must pay more attention, was simpler than expected: the environment part on which the user study was carried out is the vena cava, hence the various algorithmic calculations that gave the possibility to evaluate the distance between the virtual end-effector of PSM1 or PSM2 and, in this case, the vena cava, which by introducing it as a simple cylinder, it was possible to identify as a forbidden region all the area between PSM1 and PSM2 and the vein with a distance $d = 2.00\ cm$. From this, it is possible to identify that the region on which the virtual fixtures act is nothing more than a hollow cylinder with a radius equal to the radius of the vein and a lateral thickness of *2.00 cm.* Figure x shows how the evaluation of the FR takes place, which is possible thanks to an algorithm that has allowed us to evaluate the distance between the two objects. Hence the evaluation of the constraint evaluation within our thesis project, which, however, will not vary according to the virtual fixtures that will be applied since, as mentioned in the previous chapters, two force-feedbacks and a visual will be used, but the evaluation of the forbidden region for all will remain so.

### 3.5.2 CONSTRAINT EVALUATION

The concept that must now be discussed is how to evaluate the distance between the instrument and the patient's anatomy, in this case, the vena cava, and the importance of using triangles as the composition of our possible object and from which the identification of the forbidden region can be made. The first parameters that must be highlighted are two distances, namely the *tip distance*, which represents the distance between the vena cava and the final part of our PSM, and the *shaft distance*, with which the distance between the closest point will be identified. of the shaft tool with respect to the vein itself. The *tip distance* and the *shat distance* will be calculated thanks to a function implemented within the virtual environment so that we can define the closest point to the mesh on which we are referring. Then, thanks to this computational calculation, which will indicate the point of the tool with the minimum distance from the anatomy, it will be possible to exploit this information to define where you want to have constraint enforcement. In Unity, an object with a list of triangles and vertices is known as a mesh. The latter is an array of numbers that refers to a place in the first array, which is an array of points. You may determine the mesh's connectedness by looking at the triangles' three-by-three array of components. An *Nx3* connection matrix is produced, where each line represents a triangle and is identified by the three indices of its vertices, in order to make the connectivity structure easier to understand. This makes it simple to determine the 3D coordinates of each triangle's vertices. The meshes to which this project refers during it remain static so there are no variations during it and therefore of the triangles that compose it, even, if possible, improvement of this environment would be to create an environment a little more dynamic, as if there were in this the influence, for example, of the respiratory system. The algorithm used to identify the minimum distance between the anatomy and the tool is the Proximity Queries method, derived from the study [29], which is based on mathematical calculations to find the closest point to triangles, which in our project are the basis of the environment meshes, and works as follows: Prior to storing the nearest vertex, the distance between each mesh point and the input point is measured. In the case of broader meshes, this process might be sped up by resorting to a space partitioning technique, such as a k-d tree. After, the algorithm repeatedly looks for all the triangles that have the same vertex and are taken into consideration as candidates to hold the nearest point on the mesh. In the end, the triangle's point nearest to the input point is then located by creating a plane through its three vertices and using Unity's built-in function to find the closest point on a plane in turn: if the point falls inside the triangle, it is a candidate, otherwise, the closest point is sought on the triangle's sides. For each sub-triangle in Figure 3.6, the approach takes into account the vectors that result from computing the cross-product between $PA$ and $PB$, $PB$ and $PC$, and $PC$ and $PA$, respectively. The point is inside the triangle if every normal is facing in the same direction.

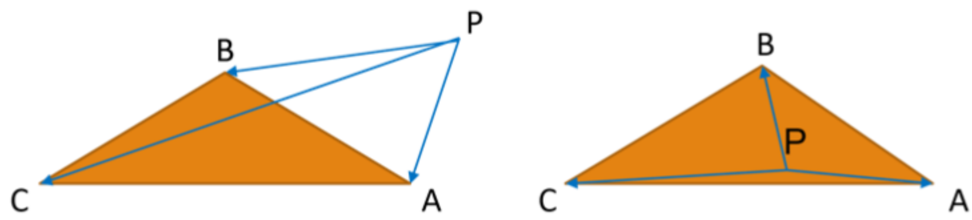


Figure 3.6: *possible position of a point*

Utilizing the projection of the point onto the segment, the nearest point is sought along the triangle's edges if the point is outside (scalar product). In turn, to identify which point of the shaft together with the tip was the closest one was done in order to divide the instrument into various small 5 mm segments to present a better calculation on the point closest to the triangles of the object considered, currently, the vena cava and this schematization of the shaft was taken as a reference by the study [15]. These processes are carried out for each of the chosen triangles, and the candidate with the closest distance to the input point is ultimately chosen to be the closest point to be given in the output. Algorithm 1 provides a summary of the mentioned procedures:

1. **For** tool's point $p_i$ do

2. Find the closest vertex mesh $v_i$
3. Initialize minimum distance $di$
4. For triangle $t_i$ with a vertex in $v_i$ do
5. Find the closest point $cp_i$ to $p_i$ in $t_i$
6. If $| p_i - cp_i | < d_i$ then
7. Save $cp_i$ as the closest point on the mesh for $p_i$ and $d_i = | p_i - cp_i |$
8. End if
9. End for
10. End for

Thanks to Figure 3.7, it is possible to observe the green line, which represents the shortest distance between the vena cava and the end-effector.

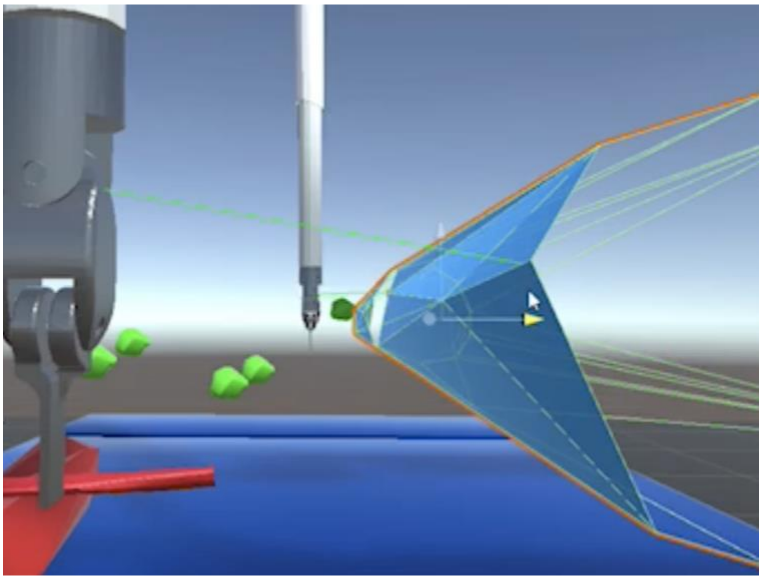

Figure 3.7: *shows the green line, that represents the distance between the cava vein and the nearest tool point*

Within the algorithm mentioned above, it was made so that if the tool was inside the forbidden region, the distance between the two objects was represented by a red line, while, as in the image above, if it were beyond the outside, it was represented by a green line.In addition to the papers that were used to obtain some useful advice for the completion of this algorithm, the engineer Martina Favaretto's approach to this project was fundamental, allowing me to get to this result, having been a tutor since her previous works were preparatory for the completion of this thesis.

### 3.5.3 CONSTRAINT ENFORCEMENT

We have evaluated how the forbidden region is defined during the possible experiments of our simulator, with which approach and methods we identify the closest point to our mesh object, the vena cava, and now the last topic to be treated is the application of the virtual fixtures. During the introduction of this thesis project, we discussed how three feedbacks were used to identify that we are in an area where tools shouldn't be. Hence the explanation of the application of our constraints, which by re-listing them are:

1. Visual feedback
2. Force feedback by visco-elastic model force
3. Force feedback by a sigmoidal function model force

The first of the listed constraints enforced is visual feedback, which was the simplest to implement and simpler to understand at the application level. This feedback application is based on the fact that the doctor during training through the simulator, thanks to the evaluation of the minimum distance of the tool from the object by means of the Proximity Queries, has the possibility to see from the main console from which he manipulates the PSMs to see them change colour if they are close to the object to be avoided. The ideology of the script created is to create a bar of colours depending on the distance between the tool and the object, which should make the doctor perceive whether or not it is close to the object when they vary. From the figures below, it is possible to observe how the colour change occurs within the forbidden region and with the approach to the object.

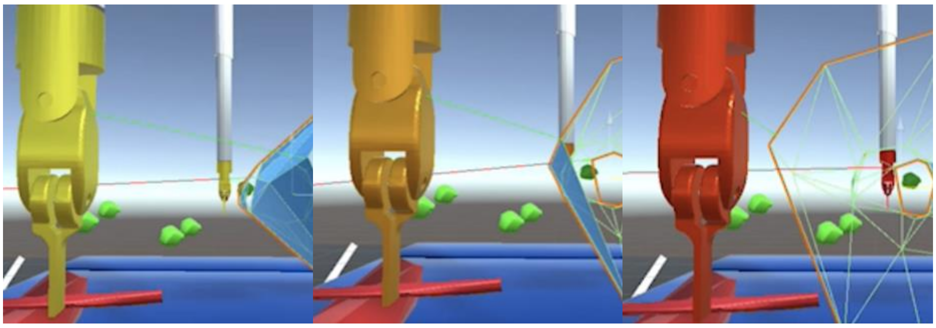

*Figure 3.8: the visual feedback with the changing of distance between the tool and the cava vein by a color bar*

It passes from the yellow colour of the end-effector at a distance of around *2.00 cm* to then becoming orange and then red as it approaches the object. This visual feedback should give the doctor the ability to better approach the moment of minimally invasive surgery with the Da Vinci, especially in the fact of a better understanding of how to observe the operating scene with the endoscope. Moving on to the study that was conducted for the application of viscoelastic force, which presents more complex concepts than visual feedback, even at the computational level in the scripts used. Moving on to the study that was conducted for the application of viscoelastic force and sigmoidal force, which present more complex concepts of visual feedback, even at the computational level in the scripts used. The first step is to define the position of the tool. That is if it is outside the forbidden region or if it is inside and everything is equivalent for both the two forces, the concept is: through a first script you go to identify the current position of the end-effector, read from the ROS topics present, and from another topic it is possible to read the minimum distance, calculated by the Proximity Query in Unity 3D, between the object and the instrument. If the minimum distance is greater than the radius of the thickness that identifies the prohibited area, i.e., *2.00 cm*, it will mean that the current position of the tool is not within the prohibited area and, therefore, it will not be necessary to apply any force and, therefore, the desired tool position If the distance were smaller, calculations would be performed to identify the necessary values of $x$, $y$, and $z$ so that the tool is outside this region and therefore the desired position in which the tool will have to be found will be none other than the actual translated position of the various $\Delta x$, $\Delta y$, and $\Delta z$ identified. The algorithm 2 present what was said is:

1. From ROS topic current position of PSM: *TP_PSM*
2. From Unity3D a topic that reads the object point closest to the tool: *point_CP*
3. From Unity3D a topic that reads the minimum distance between the object and the tool: *distance*
4. **While** (ros::ok())
5. …
6.  **If** (*distance > 2.00cm*)
7.   *Desired_position = TP_PSM*
8.  **Else**

9. *Implement_of_end_effector = 2.00cm – (TP_PSM – poin_CP)*
10. *Desired_position = TP_PSM + implement_of _end_effector*
11. …

The algorithm presents a simplification of how the script was carried out, but the concept of how to identify the "*desired position*" of the tool should be clear, and obviously with the identification of the position that the tool should be present if it were inside the forbidden region, in turn, the "*desired position*" for the PSM master tool manipulator on which the calculations are taking place will be identified. Having calculated the desired position of the tool, and consequently that of the tool manipulator, it is possible to apply force feedback if we were inside the forbidden region. The first force we are going to discuss is the viscoelastic force, which will present this scheme:

$$f = \begin{cases} k(x_d - x)\,\vec{n} + b(\dot{x_d} - \dot{x})\,\vec{n} & d < 2.00\,cm \\ 0 & d > 2.00 cm \end{cases}$$

The variable $x$ is the distance between the tool and the object, while $\dot{x}$ is its derivative, that is the nearest tool's velocity module in the direction perpendicular to the surface of the restricted anatomy. $x_d$ is the desired position that we are going to read from the previous algorithm on the calculation of the desired position, while $\dot{x_d}$ is the speed of itself, which we will evaluate equally to zero to limit the motion of the tools toward it. In order to drive the tool out of the limited zone and provide feedback on the curvature of the structure the tool is going to collide with, the force is finally applied in the same direction as the outward normal $\vec{n}$ to the surface. The force on the manipulators is set to zero when the tool is outside the restricted area. Having examined the application of the viscoelastic force, the last remaining feedback is the sigmoidal force, which was introduced by the study done on the work []. The sigmoidal force feedback is applied with the same concept used to work with the viscoelastic force, i.e., from the desired position calculated by algorithm 2, the current position of the PSM is identified and, subsequently to this, it is defined whether the force must be applied. In this brief summary, it can be observed that the only difference is that the script with which the force is applied within the forbidden region undergoes only a change in the equation of the force that is being used. To generate the sigmoidal repulsive force, the formulas used were the same as those seen in the previous chapter, which we resume:

1. $f = \frac{1}{1+ e^{-\gamma s}}$
2. $F_q' = - \frac{\partial f}{\partial d} \frac{\partial d}{\partial q}$
3. $F_q = f(q) \frac{F_q'}{||F_q'||}$

The use of these formulas will be the same as what was said during the state of the art discussing the work on which reference was made, and the same applies to the explanation for each of them. In the chapter on the results obtained, comparisons will be made on the trend of these forces, but what one can already guess by knowing the range of the functions on which one is relying is that the viscoelastic force will increase more and more as it enters the forbidden region, while the sigmoidal force will present its peak force at the boundary between the mentioned region and the safe region. Calculate the various forces, to send them to the dVRK system, they are published on a dedicated ROS topic, which allows you to set a wrench for master tool manipulators. A wrench message is composed of a three-dimensional force vector and a pair, expressed in the form of a quaternion. During this, a problem occurred. That is, when it was outside the forbidden region, the gravity compensation of the robot was not present, so the manipulators, instead of remaining in the current position, fell downwards. The gravity compensation is a command that is present by default, but the application of the scripts that imposed an impedance control for the subsequent application of the forces, caused the gravity compensation to be deactivated, and therefore it was resolved by imposing the activation of it through the publication of topics on ROS when outside the forbidden region.

## 3.6 EXPERIMENTAL TASKS

So far, in this chapter we have presented how the project of this experimental thesis was set up, with the various methods used and the deepening of the concepts, to then arrive at the formation of a general approach to the entire project. To understand if what was built could have practical advantages, experiments were carried out with 10 users who had never used the Da Vinci robot, so that it could then be seen how these virtual devices could also simplify the work for those who are not able to use this machine. This task derives from the notion that was previously discussed about radical nephrectomy, which in detail is based on an incision in front of the abdomen under the ribs, and then goes to remove the muscles, the fat, the ureter, the blood vessels, and finally the lymph nodes adjacent to the kidney to be removed. The choice to use such an operation as a reference was made because, even today, radical nephrectomy is also conducted with the Da Vinci robot, so this simulator design has the benefit of preparing doctors for certain operations. The work to be done by users was to remove the green spheres, represented by the lymph nodes, around the vena cava, represented by the malformed blue cylinder, and to locate them inside a yellow box (see Figure 3.9).

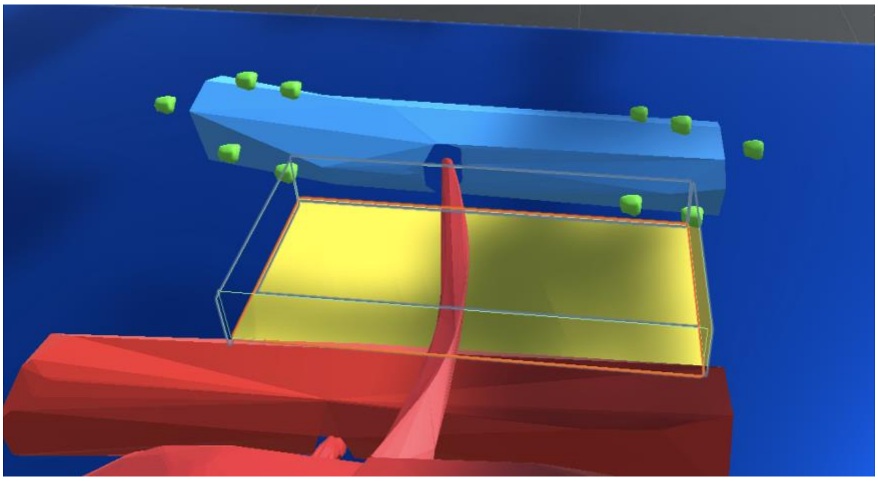

*Figure 3.9: lymph nodes, vena cava, yellow box, and a part of a Kidney in Unity3D display*

Each user performed this task six times, but with different configurations:

1. Without any feedback
2. Visual feedback
3. Viscoelastic force feedback
4. Sigmoidal force feedback
5. Visual feedback and viscoelastic force feedback
6. Visual feedback and sigmoidal force feedback

At the end of each task carried out with a different configuration, various data was collected, which will be displayed later, and then a final questionnaire was created, which was filled in by all the users who carried out the tasks, to express their opinion on the feedback used during this training and an overall evaluation of this simulator designed to improve the skills of a possible doctor with the Da Vinci

## 3.6.1 SETUP BEFORE USER TASK

Before the 10 users carried out their 6 tasks with the various feedback, it was important to prepare the workstation before each single job. So that this project could be as realistic as possible, it was made so that every person in contact with it could perceive a sense of reality during the carrying out of some experiment, to make this possible we know that the doctor who will have to operate with the Da Vinci, from the master console he can see the patient, or rather the area on which he is working, through the endoscope and since in this project he did not operate with the realistic PSM1, PSM2 and ECM, another way was found: the eyes of the user during each task are placed in the point from which you should see from the master station what the endoscope shows, and since each eye has displays, we have managed to recreate the perspective of our eyes through these two displays, i.e. when the task start from the unity scene two game screens will be transported (figures 3.10,3.11) that will represent what the user will see in the master console and the difference between them is the depth of vision, that is, if we used only the right image it would be as if we had the left eye plugged and therefore we would not be able to fully see the left side of the environment.

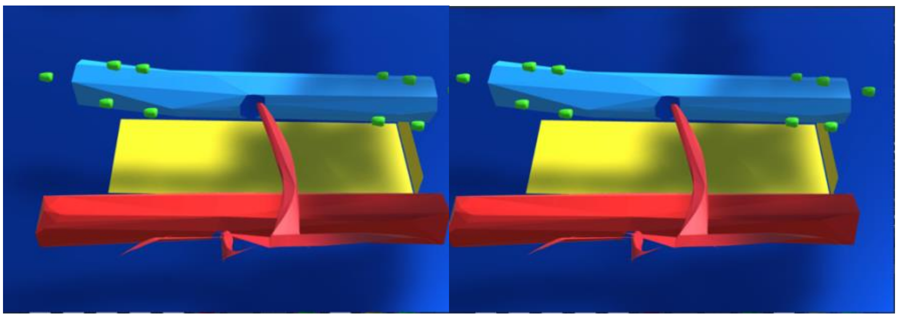

*Figure 3.10,3.11: The left image is put on the display for the left eye and the same for the right image for the right eye.*

After the game scenes on unity3D have been created, it is possible to see through figure 3.12 how they have been projected on the master console, and after that, through a main computer, every task performed by each user is monitored in order to keep an eye that nothing serious has happened.

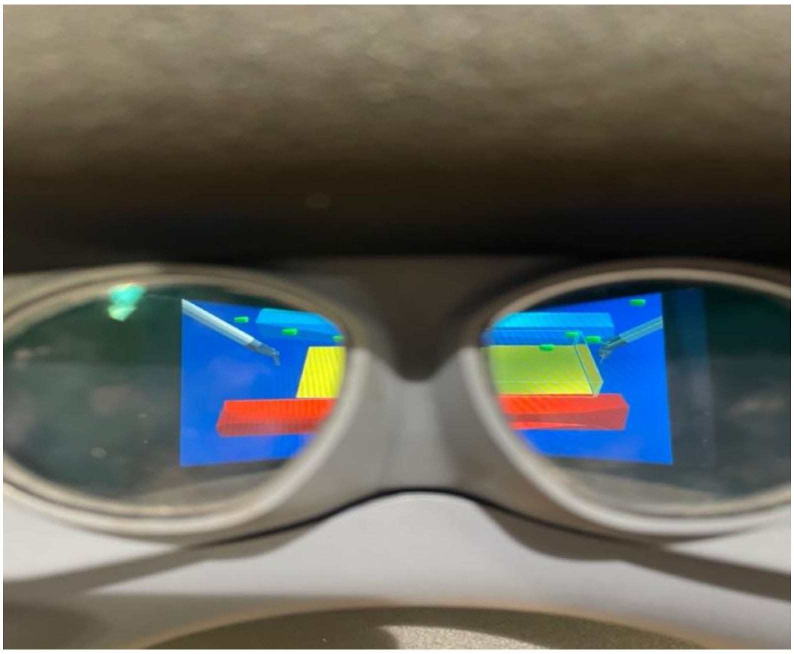

*Figure 3.12: what the user/doctor will see during any task from the master console*

### 3.6.2 PARAMETERS SELECTION

Before letting the selected users carry out the task, an evaluation was carried out on the parameters to be used in the corresponding formulas. Based on the three feedbacks used, the most important parameters used are:

- For visual feedback, the most important parameter, which can be modified accordingly, is the initial distance from the main object for which the tools begin to change their colour, and as previously said, it is *2.00 cm*.

- We have seen how the position of the tools is evaluated for the viscoelastic force. Another important parameter for the evaluation of the strength of the virtual fixtures is the elastic constant $k$, equivalent to *500* $[\frac{N}{m}]$, and consequently, the damping used through the formula $b = 2\sqrt{mk}$ , with *m* being the mass assigned to the tools for calculating force.
- For the sigmoidal force the important parameters were the $\gamma$, which after various checks carried out, it was decided to give a value of *10*, and the distance s, which was nothing more than the difference between the position of the tool, i.e. *TP_PSM*, and the closest point of the object, *point_CP*, discussed in the previous paragraphs and each of them calculated for the *x, y* and *z* axes.

An evaluation could also have been carried out on the differences that the forces would have had when some parameters changed, but the tasks to be performed would have been too numerous and therefore the values listed above were used since they were assumed to be suitable for the study conducted by this project.

### 3.6.3 COLLECTED DATA

The most important part, after each user had completed the task to be performed in all six configurations, was to collect the necessary data to be able to make a comparison between the various feedback. Among the data collected are the force values, for each axis, obtained at every single moment if it were within the forbidden region; the paths traveled by PSM1 and PSM2 during the activities carried out; all distance values between them and the vena cava; up to the evaluation of the number of collisions with the vein itself. In fact, many others data were used to observe the effectiveness of this work and to collect them csv files were created every time someone carried out a task and, depending on the task being referenced, the data that depended on it. For example, when a user used only visual feedback, it was not necessary to collect the force values he received in the MTMs as they do not exist. The collected data will be evaluated in the next chapter, which will highlight the pros and cons of each single feedback used. A questionnaire was also conducted so that each user could give a subjective evaluation for each single feedback, and this too will be discussed in the following chapter.

# 4 | RESULTS

This chapter will present the results obtained from the experiments carried out to evaluate the effectiveness of this work. Various considerations were carried out in order to better observe the characteristics of the implementing virtual fixtures, to then compare them with each other, and finally, a questionnaire was used so that each user could give his personal evaluation of the six tasks he has accomplished.

## 4.1 NUMBER OF COLLISIONS

The first result we wanted to observe indicates the number of collisions that each user made during the various tasks. Each user, as previously mentioned, has carried out six tasks, and in order to do this, thanks to a function created by scripts, it was possible to identify an approximate number of collisions that occurred between the virtual PSM1 and PSM2 and the vena cava.

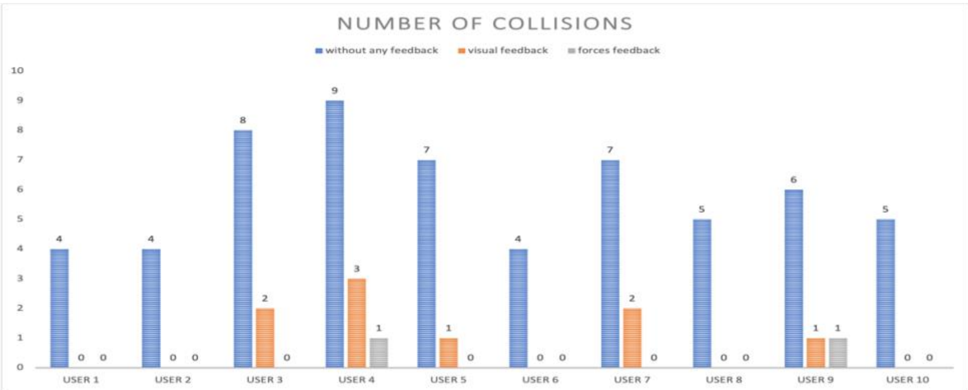


*Figure 4.1: the number of collisions by 10 users during the tasks*

From graph 4.1, it is possible to observe the trends of the number of collisions. First of all, we did not want to differentiate the collisions that occurred with the PSM1 and PSM2, so a sum was made for each task. This is because the evaluation is not based on the difference between the end-effectors but on the virtual fixtures used. It is observed that the difference between the feedback and the other feedbacks is substantial, to the point that the number of collisions occurring with the force feedbacks is so minimal for each user that the collisions with the viscoelastic force and those with the sigmoidal force. The use of these virtual fixtures shows how it led users to use different paths in order not to enter the forbidden region, and it can be deduced that the force feedback presented a better execution of the visual feedback as well, which greatly helped our users during the experiments compared to not using anything during the experiment.

## 4.2 CONTROL OF FEEDBACKS

### 4.2.1 BOX PLOT VALUTATION

In order to better observe the completion of the users' tasks, various datasets were collected, including the minimum distances between the vena cava and the tools. An evaluation method in order to show the differences between the various feedbacks was the box plot, which is a graph that presents useful parameters for the necessary observations in order to show the differences between the virtual fixtures used, namely:

- Minimum value
- Maximum value
- Median value

- First quartile value
- Third quartile value

To better evaluate the thesis project, four box plots have been created that will evaluate the minimum distances from the vein, the average distances, the overall paths and the execution times by users during the six configurations that have been conceived.

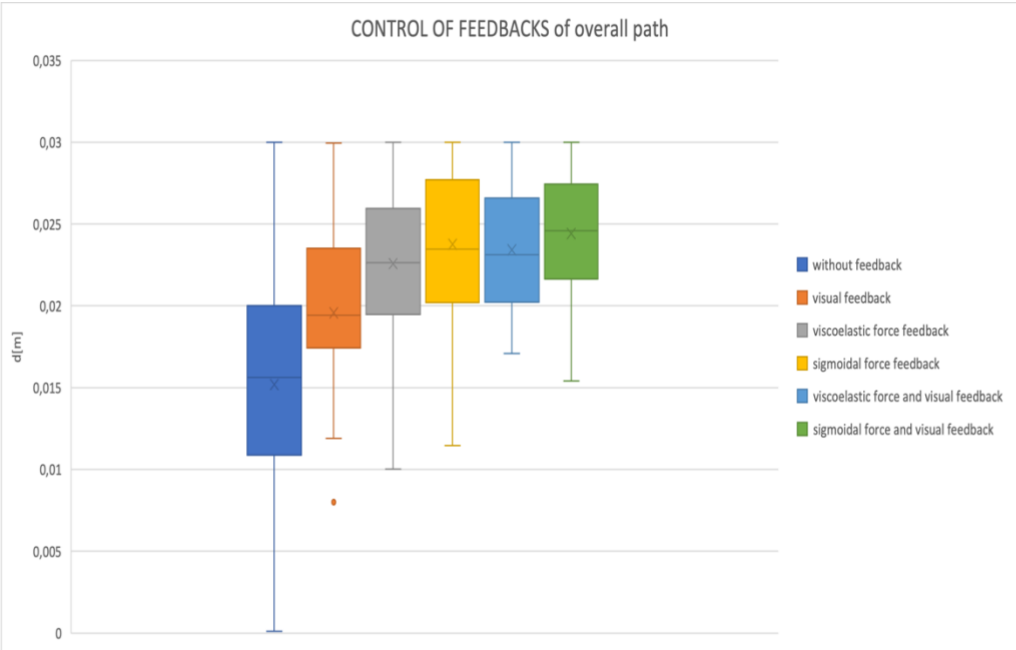


*Figure 4.2: the box plot of overall path by 10 users*

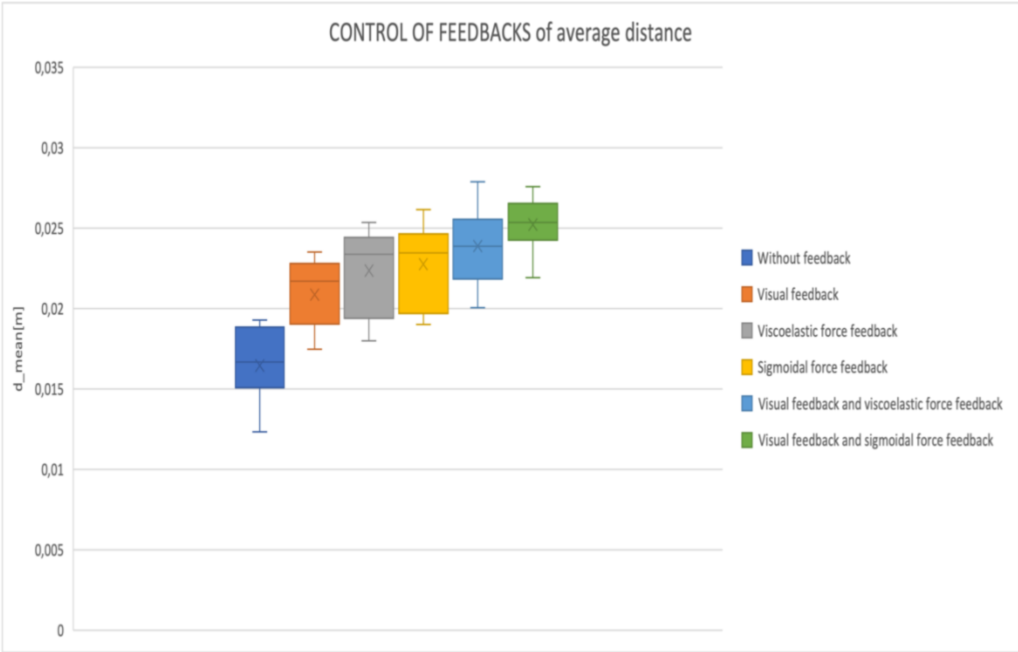


*Figure 4.3: the box plot on the average distance to the vein*

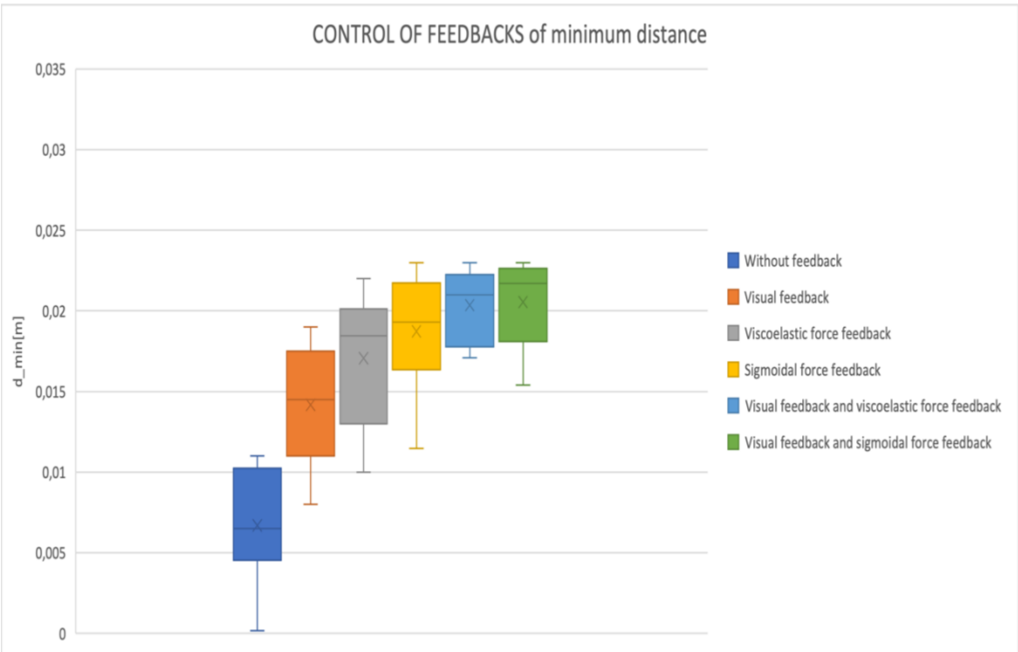


*Figure 4.4: the box plot on the minimum distance to the vein*

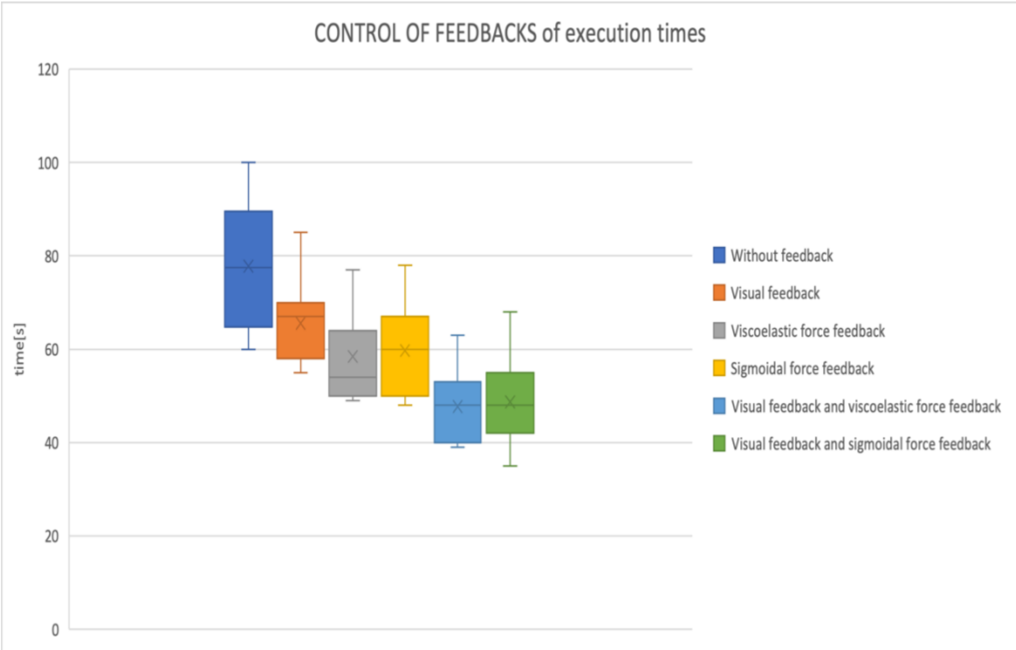


*Figure 4.5: the box plot for the six- task configurations of execution time*

The first box plot, figure 4.2, represents all the distances that the users travelled in order to perform the 6 required tasks, and in turn, no particular comments will be made. Starting to discuss the third box plot, figure 4.4, we observe from table 4.1 how the minimum distance from the object has increased with the use of virtual fixtures, especially with the sigmoidal force, which, as we will see later, will have a high force feedback MTM corresponding to the PSM, which is inside the forbidden region, little below all on the border with 2.00 cm.

| | Without feedback | Visual feedbac k | Viscoelasti c force feedback | Sigmoidal force feedback | Visual feedback and viscoelasti | Visual feedback and sigmoidal |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | c force feedback | force feedback |
| Min distance | 0,00017 m | 0,008 m | 0,0100m | 0,0114 m | 0,0170m | 0,0154 m |

*Table 4.1: The minimum distance for the six configurations*

Figure 4.3 shows the average distance covered by the 10 users during the tasks and the improvements brought about by the virtual fixtures can also be seen already, so much so that table 4.2 shows the average values of the distances hit for each configuration.

| | Without feedback | Visual feedback | Viscoelastic force feedback | Sigmoidal force feedback | Visual feedback and viscoelastic force feedback | Visual feedback and sigmoidal force feedback |
|---|---|---|---|---|---|---|
| Mean distance of mean distances | 0,0016m | 0,0213m | 0,0227m | 0,0237m | 0,0238m | 0,0254m |

*Table 4.2: The mean distance of mean distances for the six configurations*

The final box plot in figure 4.5 would represent the time it took users to complete each configuration.

| | Without feedback | Visual feedback | Viscoelastic force feedback | Sigmoidal force feedback | Visual feedback and viscoelastic force feedback | Visual feedback and sigmoidal force feedback |
|---|---|---|---|---|---|---|
| Mean execution time | 77s | 65s | 54s | 59s | 47s | 48s |

*Table 4.3: The Mean execution time for the six configurations*

From graph 4.4 but also from table 4.3, it is shown how the average value of the execution time of the requested task decreases with the use of the virtual fixtures, especially when the users have completed the work with the use of force feedback. Despite the comments on graphs 4.2, 4.3, 4.4, and 4.5, we wanted to give a greater demonstration of the validity of keeping further away from the vena cava using a non-parametric test called the Wilcoxon-Mann-Whitney test, which is often used in many studies to show differences between two samples. Without going into the specifics of the test explanation, the important parameters to know are $\alpha$, which in our case will be 0.05, and the final $p$ value obtained by comparing the distance values obtained without feedback with the others obtained in the other 5 tasks. A low $p$-value means that the result is statistically significant, while for $p$-values higher than 0.05, no particular improvements have been obtained. We observe from the tables below the various $p$-values for the samples of the box plots on the average distance, on the execution time, and on the minimum distance for all tasks:

| | Without feedback vs Visual feedback | Without feedback vs viscoelastic force feedback | Without feedback vs sigmoidal force feedback | Without feedback vs viscoelastic force feedback and visual feedback | Without feedback vs sigmoidal force feedback and visual feedback |
|---|---|---|---|---|---|
| *p* values | 0.0871 | 0.0652 | 0.0228 | 0.0225 | 0.0225 |

*Table 4.4: The p values of minimum distance for the six configurations*

| | Without feedback vs Visual feedback | Without feedback vs viscoelastic force feedback | Without feedback vs sigmoidal force feedback | Without feedback vs viscoelastic force feedback and visual feedback | Without feedback vs sigmoidal force feedback and visual feedback |
|---|---|---|---|---|---|
| *p* values | 0.0091 | 0.0062 | 0.0011 | 0.0019 | 0.0014 |

*Table 4.5: The p values of mean distance for the six configurations*

| | Without feedback vs Visual feedback | Without feedback vs viscoelastic force feedback | Without feedback vs sigmoidal force feedback | Without feedback vs viscoelastic force feedback and visual feedback | Without feedback vs sigmoidal force feedback and visual feedback |
|---|---|---|---|---|---|
| *p* values | 0.0213 | 0.016 | 0.038 | 0.0010 | 0.0027 |

*Table 4.6: The p values of execution times for the six configurations*

Thanks to these further tests that have been allowed by the use of various functions present in MATLAB, we have been able to obtain these *p* values that give us further demonstrations of the differences that our users have found during the various tasks than the task without any feedbacks. It was shown how the use of these virtual fixtures has improved the ability of users to collect the lymph nodes around the vena cava without going too close; it has also been shown how the execution time has also been improved, and in turn, how the average and minimum distances to the object showed improvements between without feedback and the other 5 configurations. In conclusion, we want to always compare the viscoelastic force and sigmoidal force feedbacks using the Wilcoxon-Mann-Whitney method when used alone or with the implementation of visual feedback:

| | Viscoelastic force feedback vs visual feedback and viscoelastic force feedback | Sigmoidal force feedback vs visual feedback and sigmoidal force feedback |
|---|---|---|
| *p* values | 0.028 | 0.039 |

*Table 4.7: The p values of minimum distance for two configurations*

| | Viscoelastic force feedback vs visual feedback and viscoelastic force feedback | Sigmoidal force feedback vs visual feedback and sigmoidal force feedback |
|---|---|---|
| *p* values | 0.022 | 0.015 |

*Table 4.8: The p values of mean distance for the two configurations*

| | Viscoelastic force feedback vs visual feedback and viscoelastic force feedback | Sigmoidal force feedback vs visual feedback and sigmoidal force feedback |
|---|---|---|
| *p* values | 0.012 | 0.016 |

*Table 4.9: The p values of execution times for the two configurations*

These last comparisons show how it is better to use two virtual fixtures than one, but in turn, a substantial difference is not noticed as in the previous tables where each value of each type of feedback used was compared with the values obtained without using any help.

### 4.2.2 ROBOT FORCES

As we said in the previous chapters, the forces used to create these force feedbacks presented different trends: the viscoelastic force was implemented in order that the users who carried out the task, as they entered more and more inside the forbidden region, always received a force from the MTMs bigger than what they could get at the border. Entering into the specifics of the experiment, we observe how, from the red box in the figure 4.5, it is possible to observe the trend of the force as the forbidden region approaches and then enters it more and more. The pseudo-linear trend of the viscoelastic force is what we wanted to obtain as feedback for users with this specific force, to such an extent that in the next paragraph we will notice how the tasks with these virtual fixtures are the ones that have had the most positive results.

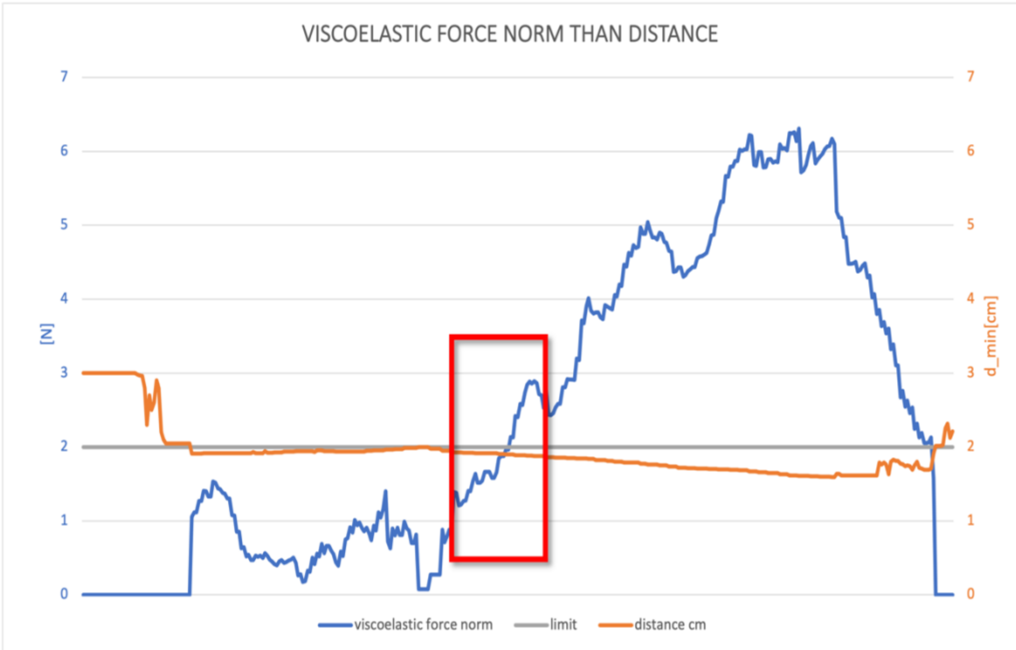


*Figure 4.6: The viscoelastic force norm than the distance from the vein*

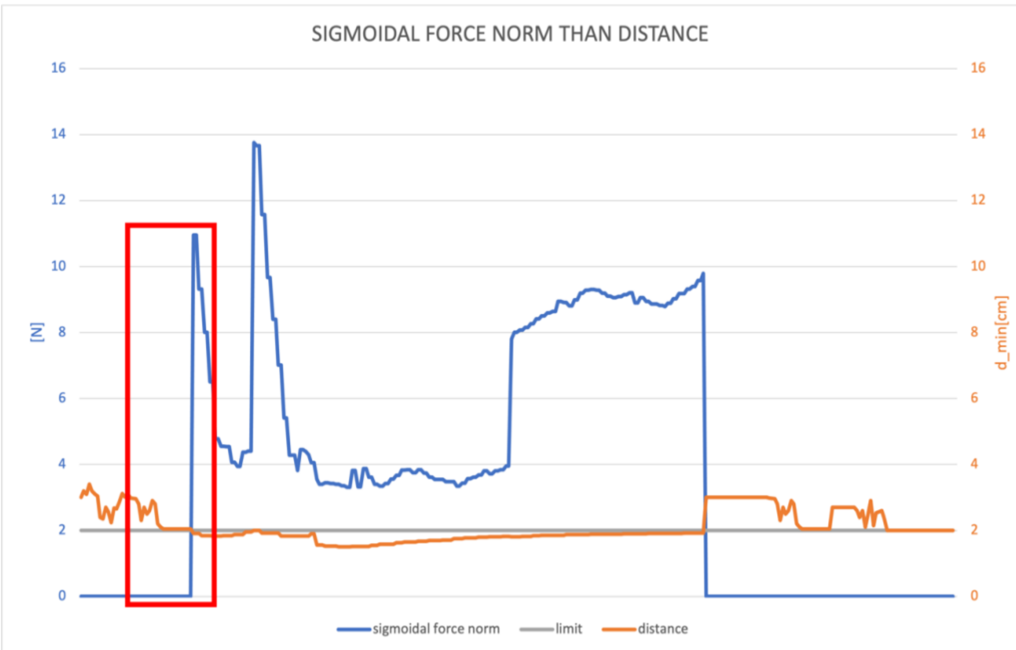


*Figure 4.7: The sigmoidal force norm than the distance from the vein*

As we observe in the figure 4.6, which represents the trend of the sigmoidal force, we see how this virtual fixture is implemented by a high force feedback at the border with the forbidden region but always within it, while as the distance from the vein decreases, the force decreases exponentially. Thanks to the red box inside the figure 4.6, you are referring to, it is possible to observe what has just been said, and after the comments made on these virtual fixtures containing these two types of forces, it is easy to observe the difference between them. Now we need to make a final observation on this topic: from the graphs, especially the one representing the sigmoidal force, it was possible to observe how the force values that the user would have heard were even higher than 5N, but this is not plausible. The Da Vinci robot presents some setups that present some limits within which the robot works, and thanks to some ROS topics related to force feedback, it was possible to observe the effective force that our MTMs received when the end-effectors were inside the forbidden region. From this, we can observe how the robot itself makes changes if the force, which can be sigmoidal or viscoelastic, is higher after the calculations on which they were based than what it can receive from setup.

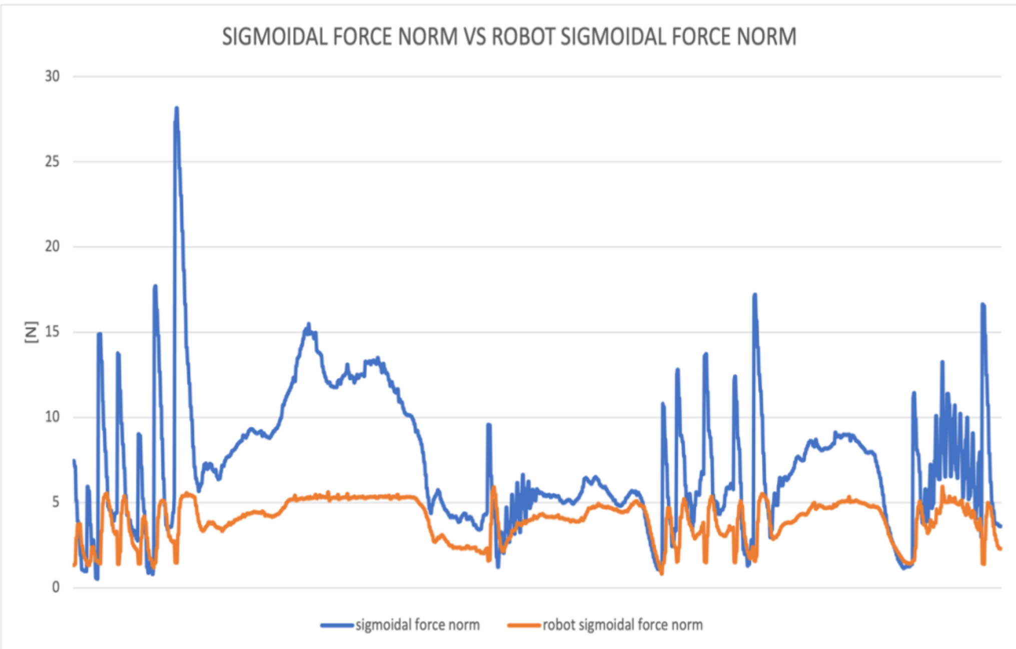


*Figure 4.8: the force feedback by sigmoidal force*

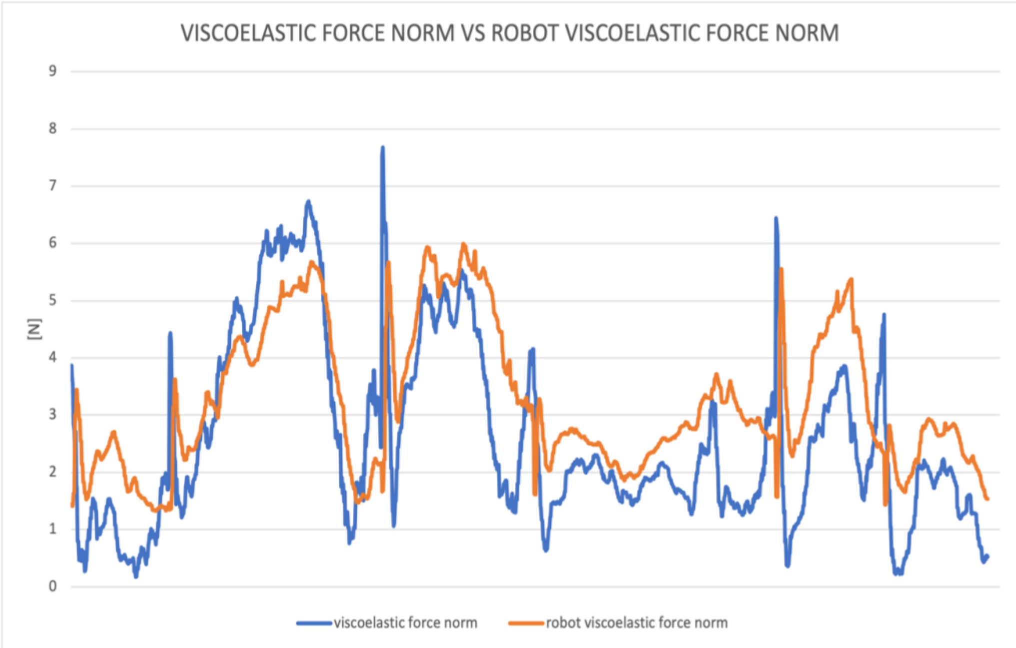


*Figure 4.9: the force feedback by viscoelastic force*

From the graphs above, we can observe the force values calculated by scripts that we would like as force feedback with respect to the actual values that users heard as they approached the vena cava, but, as it should be, we can observe that what has just been said is better observable in the graph 4.5 of the sigmoidal force, which is the one that was devised to have the greatest contrast at the border with the forbidden region. Finally, it can be observed that the robot does not accept force feedback values higher than 6 N.

## 4.3 QUESTIONNAIRE

### 4.3.1 QUESTIONNAIRE SETUP

The questionnaire that was proposed after completing the six tasks presented this configuration: It is necessary to give a value from 1, which indicates *"strongly disagree"*, to 5, which indicates "*strongly agree*", on 10 questions repeated for all 6 configurations, and other considerations have been made based on the subjective thinking of the user. The table below represents the questions that were asked during the questionnaire for all types of experiments:

| |
|---|
| I think that I would like to use this system frequently |
| I found the system unnecessarily complex |
| I thought the system was easy to use |
| I think that I would need the support of a technical person to be able to use the system |
| I found the various functions in this system were well integrated |
| I thought there was too much inconsistency in this system |
| I would imagine that most people would learn to use this system very quickly |
| I found the system very cumbersome to use |
| I felt very confident using the system |
| I needed to learn a lot things before I could get going with this system |

## 4.3.2 RESULT OF QUESTIONNAIRE

The questionnaire that asked the 10 questions to the users was a great success because everyone appreciated the system that was designed, and above all, they found benefits in carrying out the tasks with the use of virtual fixtures. The graph 4.7 is an example of the results found by the questionnaire, so much so that when asked if they would like to use this system frequently, it is easy to observe how each user has observed a noticeable improvement with the use of both visual feedback and forces feedback, even if the latter received more positive evaluations, and the same applies to the tasks performed with the use of both proposed feedbacks.

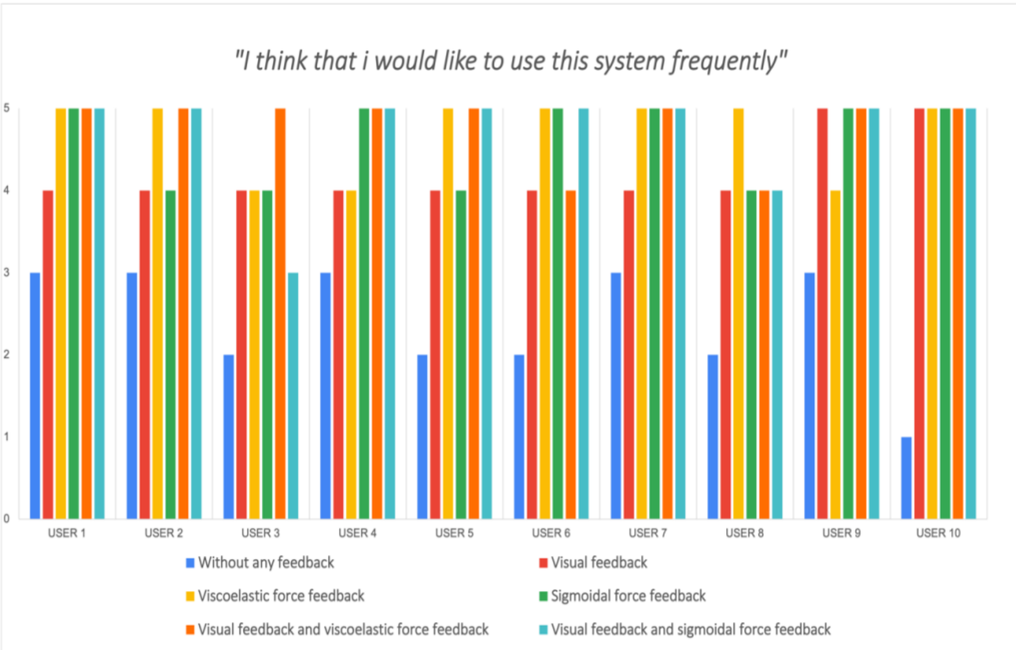


*Figure 4.10: the results of the first question of the questionnaire*

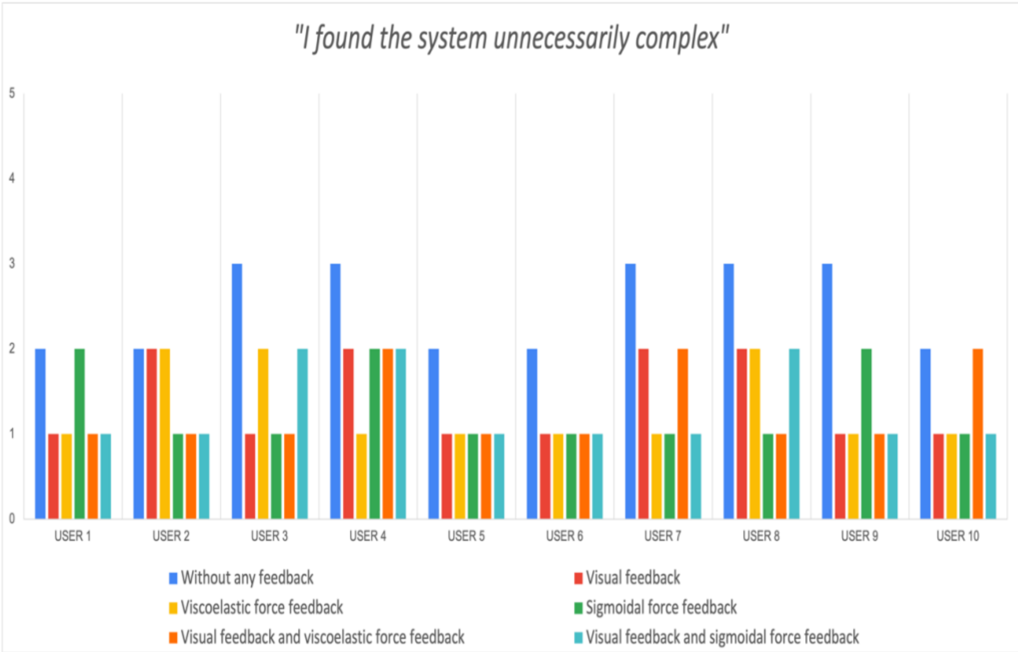


*Figure 4.11: the results of the second question of the questionnaire*

The 10 questions were divided into 5 positives and 5 negatives. In fact, if we first wanted to observe one of the results of the positive questions, now we will show a result of the negative questions. When asked if this system was found unnecessarily complex (see graph 4.10), most users replied "strongly agree" to the task performed without feedback because they found it difficult to avoid the vein during the completion of the experiment, while with the use of feedback beacons they found it easier to carry out and, in turn, the implementations of the various virtual fixtures did not create problems of system complexity. Another considerations will be made on the maximum value that could be given in the questionnaire, which is *"strongly agree",* regarding the feeling that was felt during the tasks, and it is possible to observe that most of the users felt more comfortable with the use of multiple virtual fixtures, so that from the graph 4.11, it is possible to observe how visual feedback and viscoelastic force feedback and visual feedback and sigmoidal force feedback were the tasks that received more fives in question 9 of the questionnaire.

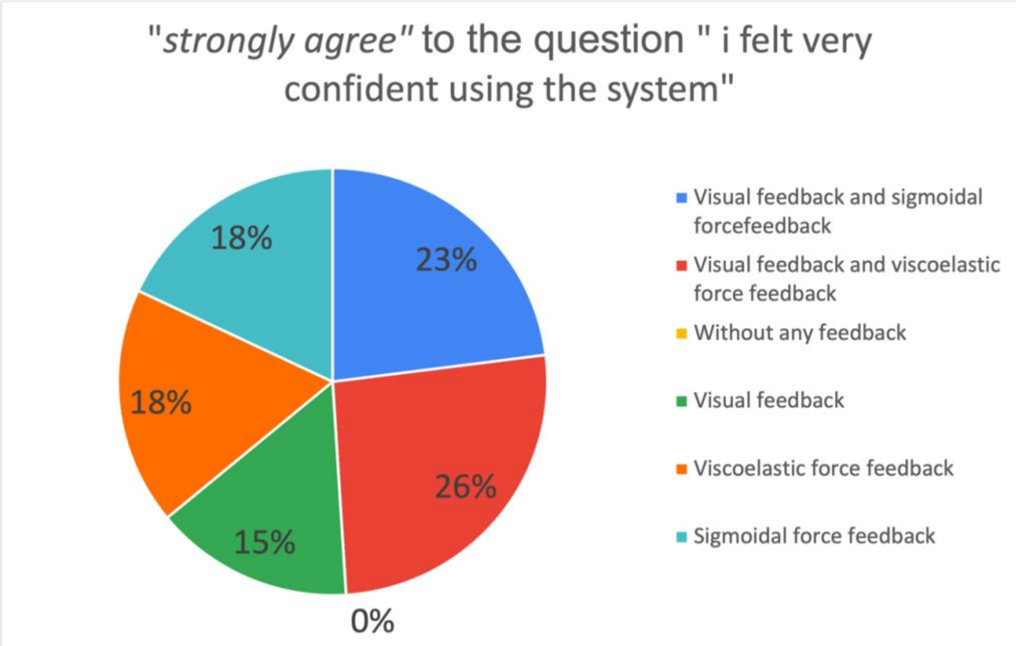


*Figure 4.12: the results of the third question of the questionnaire*

The last consideration on the results obtained is based on the SUS (System Usability Score), which has become a well-used evaluation method over the years and therefore also derives the choice of having composed a questionnaire of positive and negative questions with the choice of giving an answer with a value of 1 to 5 (1-strongly disagreement to score 5-strongly agreement). the equation used for the calculations of the latter graph is:

$$SUS = \left( \sum_{i=1,3,5,7,9} (S_i - 1) + \sum_{i\,=\,2,4,6,8,10} (5 - S_i) \right) * 2.5$$

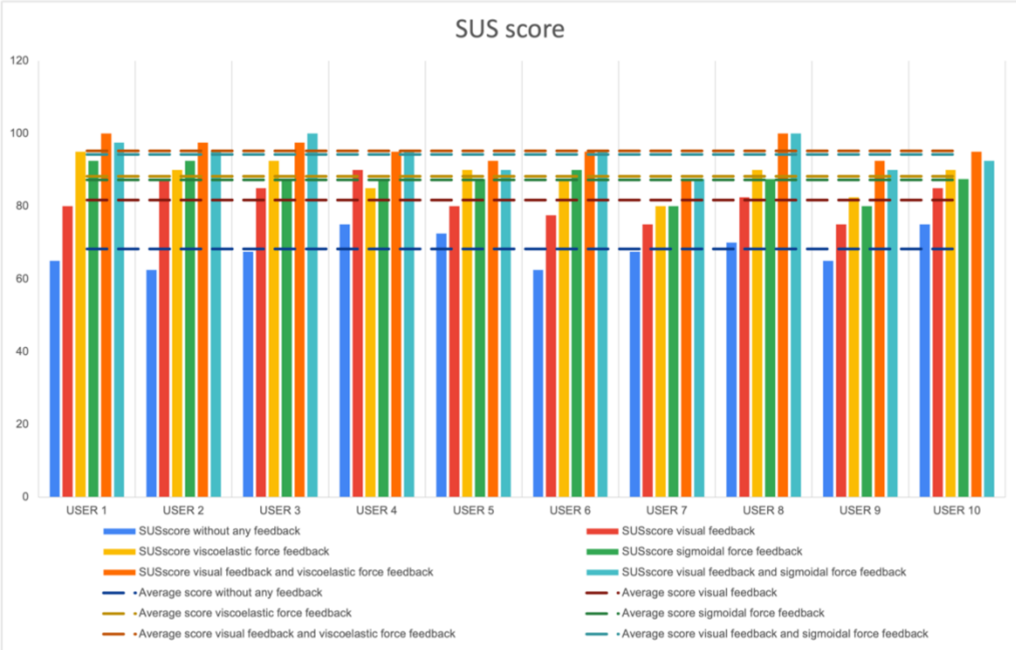


*Figure 4.13: The results of SUS score*

From the last graph, it is easy to see how users reacted to the questionnaire as a whole. It is possible to observe how the average value for without feedback is 68.25, for visual feedback it is 81.75, for viscoelastic force feedback it is 88.5, for sigmoidal force feedback it is 88.25, for visual feedback and viscoelastic force feedback it is 95.25, and for visual feedback and sigmoidal force feedback it is 94.25. In conclusion, it can be noted that among the tasks with the use of visual feedback, viscoelastic force feedback, and sigmoidal force feedback, users preferred the second of those listed, and in turn, the implementation of viscoelastic force with visual feedback is that combination with a higher SUS score than visual feedback with sigmoidal force.

# 5 | DISCUSSION

In this last chapter, we will deal with the characteristics of this thesis project, and, in turn, what could be improved in the future.

## 5.1 SETUP OF DA VINCI ROBOT

In the previous chapters, we have seen how the robot was prepared in order to carry out the user study. Having given the possibility to each user to see from the master console what has been devised on Unity, as mentioned above, has allowed to increase the reality of the experiments; nevertheless, there is a consideration that should be made on this.

*Figure 5.1: a Master console of Da Vinci robot*

From figure 5.1, a possible master console can be seen better than in the past images, which show pedals that can be used by the doctor. One of the pedals is called "clutch", which has a fundamental role during operations, that is, from the various images of the master consoles it is possible to observe how the MTMs could afford to move in a well-defined area, so when one is at the limit of how much you can move an MTM but it is necessary to move the corresponding PSM again, pressing the foot-pedal clutch will make it so that we can return the MTM to an initial position, leaving the PSM at the point where it was before pressing the pedal, In practice, by pressing the clutch pedal while holding it down, the communication between the MTMs and PSMs is disconnected. A possible improvement that could be made to this thesis project would be to increase the size of the work environment for the required tasks in order to also implement the use of this pedal and make the possible training by doctors even better for novices who could practise with this job.

## 5.2 ENVIRONMENT IMPROVEMENTS

The environment that has been created has allowed us to perform adequate tasks to show the project we have worked on, but in the future, we could try not to simplify the models created on Blender and make sure that they can be as defined as possible. The simplification, as mentioned in the past, was made because the high computations by the scripts between the various triangles with which a mesh designed by Blender is composed caused a lot of delay during the various tests, and hence the choice to reduce the triangles with which the models of the project were composed. Finally, a solution to this could be the use of more innovative instrumentation (computers, various connections, etc.), or improving the various scripts that allow the project to be carried out to the point of being able to reduce the number of them to make sure that there are not too many calculations that the various computers, programming systems, and ROS connections have to face.

## 5.3 WILCOXON-MANN-WHITNEY TEST

The Wilcoxon-Mann-Whitney method was useful to demonstrate with a non-parametric statistical method that it showed the effectiveness of the results obtained from the various virtual fixtures. In the previous chapter, there was a brief explanation of how to interpret the $p$ value, which in each comparison carried out presented excellent results, always less than 0.05, but in turn with the last three tables, i.e., 4.7, 4.8, and 4.9, it was shown how even slight improvements were easily found between the tasks carried out with one of the two forces compared to the task with one of the forces, but with the implementation of visual feedback, and obviously the $p$ values obtained were not minimal like the comparisons made with the task without any feedback.

## 5.4 FORCES SHAPE EXPLANATION

Both the viscoelastic force and the sigmoidal force have shown excellent results when they have been used during the required tasks, and users have also given positive feedback to these virtual fixtures. Nevertheless, a negative consideration that these virtual fixtures present within this thesis project is the direction they take in some points; in fact, one could try to better improve the direction of the force feedbacks by finding a better relationship for the purpose than in all points where the end-effector is in the forbidden region, the corresponding MTM will receive feedback that moves it in the correct direction in order to exit the red zone. This is the only consideration that could be done on these virtual fixtures, and the way in which they were implemented allowed to obtain the results shown in the previous chapters.

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# List of Figures

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