DESIGN AND DEVELOPMENT OF A HAPTIC FEEDBACK CONTROLLER FOR ENHANCED PRECISION IN MRI- GUIDED BIOPSIES USING THE SUNRAM 7

N. (Nick) Kompagnie

BSC ASSIGNMENT

Committee:
dr. F.J. Siepel
dr. V. Groenhuis, MSc
dr. ir. D. Reidsma

July, 2023

032RaM2023
Robotics and Mechatronics
EEMathCS
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Abstract

This study presents the design and development of software used for a haptic feedback controller, specifically tailored to the Sunram7 robot. The aim of this research is to improve user experience and biopsy accuracy. Methods to develop such a system are explored.

MRI-guided biopsies play an important role in determining the malignancy of a lesion found in breast tissue. When a biopsy is done, several factors influence the precision and accuracy of the needle placement. To minimize the effect of these factors, a prototype of a haptic-enabled robotic system is built to provide feedback to the user to improve control.

The study investigates several subquestions to support the research goal. First, relevant safety features are identified and implemented to ensure the safety of the user and patient. Secondly, the design process will focus on conveying important information to the user through haptic feedback. Results indicated that users achieved an average error of 3.06mm when hitting the targets, and the maximum system delay measured was 100ms. Finally, user tests were conducted to assess the perceived usability of the controller. The feedback received through a survey indicated a usability rating of 6.25/10.

Contents

List of Figures

List of Tables

1 Introduction

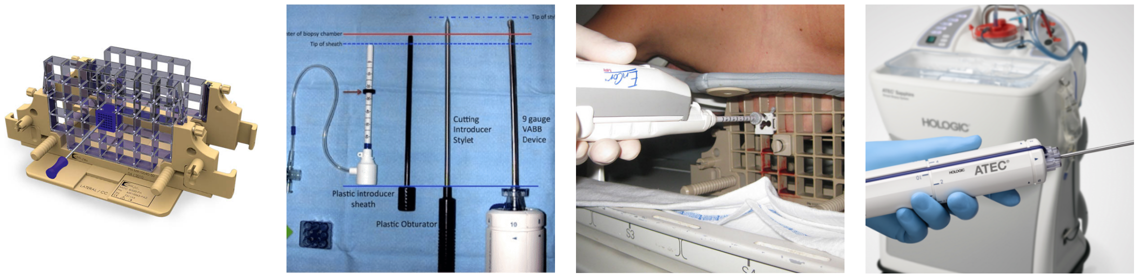
Breast cancer has been the most prevalent cancer worldwide for the past few years. This form of cancer contributes up to 12.5% of all cases [26]. Preventive screening methods have been effective in reducing the mortality of this disease [15]. To accomplish this, multiple imaging techniques can be used. Most common techniques are MRI, ultrasound and CT. When a potential breast malignancy is detected, a biopsy is often necessary to determine if the abnormality is cancerous. The most commonly used method for guiding the biopsy needle to the malignancy is the use of ultrasound. This method is fast, non-invasive, and often much cheaper than other methods. Some malignancies are however not visible using this technique, while they can be found with MRI techniques. This is why MRI-guided biopsies are currently the gold standard. In this case, an MRI-guided biopsy is often chosen.

1.1 MRI Biopsy procedure

To start the MRI-guided biopsy procedure, technicians prepare the equipment. Since it is beyond the scope of this research to present different commercially available systems, the general workings of every component will be explained, and how the technicians operate them.

First, the patient is expected to come in having fasted prior to the medical procedure. The patient is laid down and the breasts are passed through the interventional breast coils. With two open spaces for the breasts to pass through, interventional breast coils are designed to specifically image breast tissue in the MRI machine. After that, a localizing device, consisting of two grid-structured plates visible in Figure 1(a), is placed to fix the breast tissue in place and to provide a localizing reference for the Computer-Assisted Diagnosis System. This system digitally calculates the required entry site and needle depth to reach the chosen site on the shown images. In the previously placed grid, markings are made in where the guiding block, which can be seen on the lower right in Figure 1(b) can be placed to perform the biopsy through.

The entry site is cleansed and numbed, after which a coaxial biopsy system is used to perform the biopsy. This works by inserting a large metallic stylet into the tissue, this creates space for a plastic guide tube with depth markings. After the tube is placed, the patient is scanned again to confirm that the tip of the tube is at the correct position in the tissue. To take a sample of the tissue, a vacuum device is inserted through the tube to cut away small pieces of the tissue by slowly rotating the device. The tip of the needle has an opening into the side with sharp edges, which cut the tissue while rotating. The cut tissue passes through the needle and is caught by a metallic strainer at the end of the device. These tissue samples are taken out and further investigated. The entire vacuum-assisted biopsy system is shown in Figure 1(d).



(a) (b) (c) (d)

Figure 1: Equipment used for MRI Vacuum-assisted breast tissue biopsies (a)Grid structure [16]. (b) MRI equipment consisting of a plastic introducer sheath, obturator, Introducer Stylet and VABB device.[8]. (c) Biopsy taken [14]. (d) Vacuum-assisted biopsy needle [11].

While being considered the gold standard, the procedure does have some disadvantages. Patients need to be scanned four times, the first for the base image, a second time with contrast fluid injected, the third time to confirm the correct insertion of the marker, and the last time to check whether actual tissue of interest has disappeared. A large portion of the total procedure time is taken up by this. Patients can be expected to be in the MRI room for up to one hour. In addition, the vacuum-assisted biopsy device needs a rather large insertion hole to perform. Although the patient has a local anesthetic, the biopsy is perceived as painful and uncomfortable. The previously described method only allows for lateral insertion, so if a possible malignancy is medial relative to the entry site, the needle needs to pass through a lot of tissue [3].

1.2 Robot-assisted MRI-guided breast biopsy

To address the limitations associated with the current methods used in MRI-guided biopsies, the Robotics and Mechatronics (RaM) group at the University of Twente has developed a range of innovative robotics solutions. These solutions were designed to overcome the challenges posed by the powerful magnetic field generated by the MRI machine, which restricts the use of metallic, ferromagnetic, or conductive materials [22].

Figure 2: Sunram7 Biopsy Robot

The conventional electric motors commonly used for actuation cannot be employed in this environment. To overcome this limitation, Groenhuis designed and tested pneumatic actuators specifically suited for operation within MRI environments [9].

The 7th iteration of this robot is the Sunram7. This 5-DOF robot can accurately insert a needle into soft tissues in strong magnetic fields such as that of MRI environments. The current controller, designed for research purposes, consists of a board with joysticks with each direction assigned to a single stepper motor.

1.3 State of Art Analysis

A recent study at the University of Technology in Cyprus looked into how well robotic devices can move and accurately target needles in an MRI environment [1]. They used special models to measure accuracy in a breast phantom. The development of the robot utilized in the testing phase was carried out as part of the FUSROBOT project at the University of Technology in Cyprus.

One important thing about this robot is that it can be used in an MRI machine, but it needs electricity to work properly. This means it is considered ”MR conditional.” The study assessed the impact of the robot's presence, which was found to be negligible, with only a 2.5% effect on the signal-to-noise ratio.

The mechanical stages of the robot were capable of moving with an accuracy of 0.1mm. However, when integrated with the MRI system, various other factors introduced errors, resulting in an overall achieved accuracy of 1mm. The study suggests that for lesions measuring at least 3mm, the system would be sufficiently accurate for practical use.

A study from 2017 on liver biopsies introduced a new method of providing haptic feedback to the user. The researchers utilized a hydrostatic transmission technique to allow surgeons to insert a biopsy needle while the patient remained inside the MRI machine. The study found that when the surgeon manipulated the needle at realistic speeds, the force perceived by the user closely matched the actual force measured on the needle. Importantly, this system had minimal impact on the quality of the MRI images, and it was considered cost-effective as all the components were passive. Furthermore, this system operated independently of the imaging system used. The study concluded that manual biopsies performed using this system were equally accurate compared to traditional methods. Additionally, the researchers suggested that utilizing such a system could potentially expedite the entire procedure, as it eliminates the need for the patient to move in and out of the MRI machine [7].

1.4 Tracking methods

To track an object in 3D space, several techniques have been developed. This subsection describes several possibilities that will be analyzed later in this report for use in this research. This is relevant for this research since tracking methods will be used to build the controller.

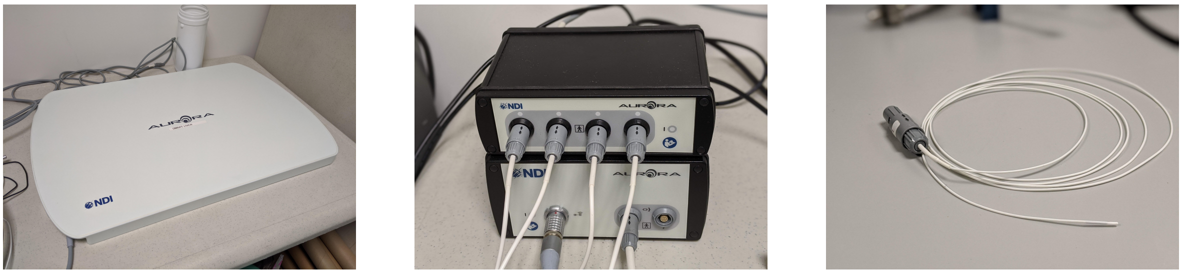
1.4.1 Optical Tracking

Optical Tracking Systems (OTS) can determine the location of an object by calculation of images from multiple camera sensors. With this method, high accuracy can be achieved. OTS is generally considered robust to environmental factors, because the cameras can be in a fixed position, and are not affected by environmental factors such as pressure and temperature OTS requires a direct line of sight to the object to be able to correctly determine its position [21]

1.4.2 Electromagnetic Tracking

An Electromagnetic Tracking System (EMTS), consists of several parts. An electromagnetic field generator, electromagnetic sensors, and a control system. The electromagnetic sensors consist of some coils which voltage is induced upon. This voltage is measured and can be used to determine the position of the sensor. This type of tracking is strongly influenced by external electromagnetic factors. Jewelry and nearby electronics can impact the ability to accurately determine positional data.

Furthermore, since the EM-field generator, shown in Figure 3a, has a finite size, the workspace of this system is limited. The sensors, which come in different sizes an shapes, can be manufactured relatively small, which is an advantage in case of a device design [6]. An example of such a sensor is shown in Figure 3c.



(a) EM field generator (b) Control module (c) Sensor

Figure 3: Basic equipment for EM-tracked devices [25]

1.4.3 Linkage tracking

Another way of tracking an object in 3D space is to connect the object to several hinged links. At the joints, measurements can be done on the current positional angles. Using kinematic calculations, the position and/or orientation of the object can be determined. The degrees of freedom that can be measured depend on the setup. The accuracy of this type of system is high since multiple sensors can determine the position and thus the result can be validated. These types of systems are often self-calibrating and not influenced by environmental factors. The disadvantage is the range of motion. Since the links connected to the object are fixed, this range is predetermined.

1.5 Haptics

With upcoming robotic solutions for healthcare, researchers are looking for ways to control these robots. To simulate reality, the robot controller needs to convey real-time information to the operator. The operator can for example see the robot and the patient through a camera, hear sounds through a speaker, and communicate with the present staff through a microphone. In a lot of situations, the sense of touch can contain important information for the surgeon. This is where the subject of haptics comes in. This technology can simulate the senses of touch and motion to reproduce sensations that would be felt if the user would directly interact with the physical objects [18]

The challenge of implementing haptic feedback on surgical robots is often the controller stability. Due to this, many developers opt for different, external information flows to the surgeon like vibrotactile, auditory cues or visual information [19].

1.5.1 Tactile

Tactile sensing deals with mechanical properties that can be sensed on a skin level. Textures, shapes, viscosity and shear for example resistance are all things that humans can detect by receptors in the skin of for example fingertips. The ability to sense these things can be of great importance during precise surgical tasks. In remote surgery, this kind of sensation can be simulated by vibrations, and pressure changes. The advantage of this technique is that these types of systems do not influence the control stability of the robot, since they can be sensed externally [20].

1.5.2 Kinestetic

Kinesthesia, more commonly described as the feeling of displacement, is typically simulated by applying forces on the body. This type of haptic feedback is perceived through tendons, muscles, and joints, and it plays a crucial role in creating a realistic sense of touch. With kinesthetic feedback, it is crucial to measure the transparency of the system, which refers to how well the feedback system represents reality. Factors such as delay and accuracy can introduce misrepresentations or even cause oscillations in the control system. Therefore, monitoring the influence of kinesthetic feedback on the control system is essential to ensure safety [20].

Research studies have shown that using a haptic feedback device with a robot to exert forces provides greater accuracy when kinesthetic feedback is incorporated [13]. The survey conducted by Lim et al. demonstrated that user experience improves significantly due to the added sense of realism.

1.6 Problem definition

After understanding the current biopsy procedure, the development of the Sunram7, and different options for haptic feedback, the question arises if haptic feedback can be implemented on the Sunram7 robot, to improve accuracy and user experience. As of right now, the robot does not have the capability to sense forces on the actuator and send it back to the user interface. Since implementing this sensing capability is outside the scope of this research, a simulation will be done to mimic this type of experience.

The accuracy of these biopsies is important for several reasons. The first has to do with the invasiveness of the procedure. To perform a biopsy, a relatively big needle had to be inserted into the tissue. Repeatedly performing this procedure due to inaccuracies could potentially cause additional harm to the patient. A second important reason for accuracy is that inaccurate biopsies increase the chance of false negative results. This could become dangerous for the patient since no further treatment will be advised and would result in a higher mortality chance.

The main research question is:

How can software for a haptic feedback controller be made for the Sunram7 Robot to enhance precision and improve the user experience for a simulated scenario?
Several subquestions help answer the main research question:

- What are the relevant safety features necessary for the haptic feedback controller implementation on the Sunram7 Robot, and how can they be effectively integrated?

  When designing medical systems, safety is a critical aspect. The aim of this subquestion is to identify the safety features necessary to design a safe controller.

- How can haptic feedback about the needle path, tissue properties, and other relevant factors be conveyed to the users?

  This subquestion works out how the feedback can be calculated, conveyed and interpreted.

The performance of this system is tested following these questions:

- What level of accuracy can the user achieve when using the haptic feedback controller for the simulated scenario of hitting targets?
- What is the total delay introduced by the software system when providing haptic feedback to the user?
- How is the usability of the haptic feedback controller system perceived by the user?

Figure 4 provides a visual representation of the overall system and illustrates its position within the entire setup.

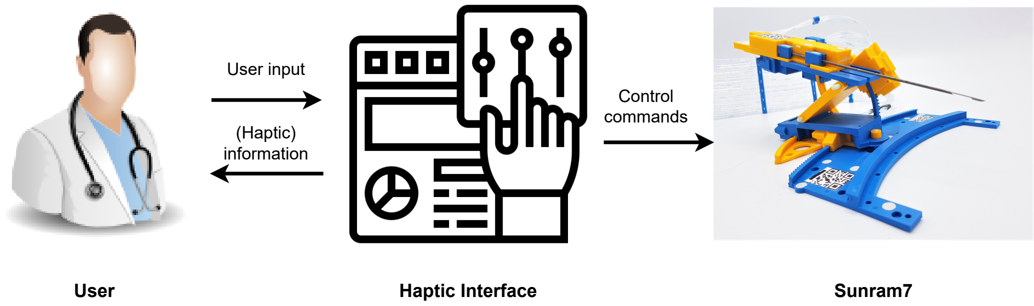


Figure 4: User Interface in the system

2 Stakeholder-Driven Requirements and Concepts

To determine the appropriate requirements, conducting a stakeholder analysis is important. Firstly, the various stakeholders will be discussed, followed by an interest and influence analysis. With this information, requirements can be constructed. To compare different options, concepts will be generated and evaluated.

2.1 Identification of stakeholders

The end users are the main stakeholders in this research. These stakeholders are the ones that actually will make use of this product in its final form. The patient will be the most important stakeholder since the main goal of healthcare is to provide a better quality of life to the patient. To accomplish this, the surgeon or practitioner will utilize this system. Therefore it is important to consider the requirements of this stakeholder.

Next to the users, the secondary stakeholders need to be considered. These stakeholders are involved in the process of getting this system to the end users. The first of this subgroup are the implementation stakeholders. This can for example be the manufacturers, supply chain engineers, governing bodies or marketing experts.

The support stakeholder do not play are large role in this research, but for completeness, they will be considered. The main goal of support stakeholders will be to assist the engineers and designers in all sort of ways. Examples are students, translators and technical staff.

The last of this column are the expert advisors. These advisors play a major role in the developement of a system by providing knowledge gained by experience to the design engineers [4].

Table 1: Stakeholder overview

User stakeholders	Secondary stakeholders
Patient	Implementation stakeholders
Surgeon	Support stakeholders
	Expert advisors

2.2 Interest and influence analysis

2.2.1 Patient

First, the interests and influences of the patient are analyzed. Since the procedure assisted by the robot is performed on the patient, the patient's main interest is safety. The product should never bring any unnecessary harm. Next to safety is the time of the entire procedure. If the total procedure time can be decreased, the patient has to spend less time in the hospital. One of the main goals of this research is to minimize the invasiveness of the procedure, as it is crucial for both patient comfort and overall treatment outcomes.

2.2.2 Surgeon

For the surgeon, safety is also a factor. The surgeon should always be safe while performing the biopsy. Time factors also play a role for the surgeon, because with lower time per biopsy, the surgeon can work more efficiently and possibly focus more time and energy on other tasks, thus improving the healthcare provided. Since the surgeon will be using this system as a tool, easy of use is a major part to consider. Ease of use can be divided in to several subparts. The first part is the ease of use. It would be of great benefit to the surgeon if the controls of the robot are intuitive, and would not require much training. If controls are not easy enough, there is a possibility that the system would be rejected by the end user and that another system would be preferred.

2.2.3 Secondary stakeholders

The secondary stakeholder will be shortly discussed in this paragraph. Due to the relatively small scope of this assignment, these stakeholders are less relevant. To keep perspective on the goal of this assignment, they will be considered. The first secondary stakeholder mentioned in table 1 is the implementation stakeholder. During the process, the feasibility of implementation should be considered to meet the needs of these stakeholders. This can for example be done by using readily available, and/or easy-to-manufacture parts with common materials if possible. Since the goal of this assignment is a working prototype, this is less relevant. Doing an analysis on the support stakeholders does not provide much insight too, again due to the relatively small scope of this project.

Table 2: Overview of table contents: The first column displays the different categories of requirements, while the second column provides detailed information about each requirement.

Category	**Requirement**
UI design	With the UI, the surgeon must be able to perform a biopsy for MRI-breast malignancy screening
	The user interface must have an input controller which the surgeon can steer in 6DOF.
	To enable manual control of the Sunram7, the UI must be able to retrieve information from the surgeon
	The user interface should have the functionality to customize controls based on individual wishes
	Ensure that the ergonomics of the User Interface are taken into account
Input translation	The user Interface should be able to translate these inputs to control signals for the Sunram7
	Filtering and normalization of signals
Haptic feedback	The user interface should be able to provide haptic feedback to the user.
	Adaptive feedback based on tissue properties
Safety and Risk mitigation	The device must never cause harm to the end users
	An emergency stop button should be implemented.
	When the user interface fails, the robot should stop in a safe manner.
	Disabling certain degrees of freedom should be a possibility for the end user.
Usability and Training	The surgeon should understand the way of controlling the device within 10 minutes.

2.3 Requirements

To keep track of important goals in this research, requirements have been set. These requirements are displayed in Table 2. The final system will be evaluated partially according to these requirements.

2.4 Concepts

With the problem description, stakeholder analysis, and requirements in mind, several options will be considered in this chapter. From the tracking and haptic options described in the introduction, several concepts will be constructed. In addition, the commercially available options are considered for this project. After all this, an evaluation will be done to choose the best option for the scope of this project.

2.4.1 Concept 1: Optically tracked haptic device

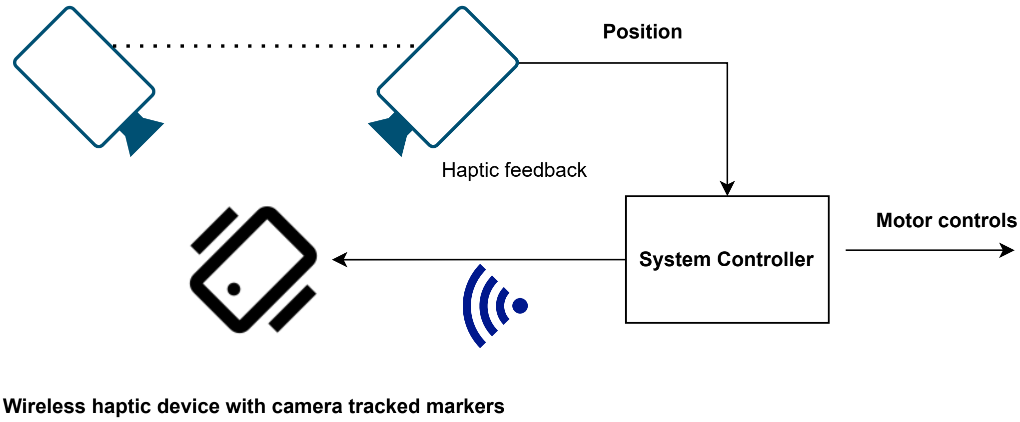


Figure 5: First Concept

The first concept consists of a camera-tracked handheld device. A major advantage of this system is the large workspace. Cameras will be set up in the room which can track markers on the handheld device. These cameras do need calibration beforehand.[23] When the positional and orientation data are sent to the controller, it can interpret these signals into motor signals and push haptic feedback to the handheld device. Since this device is not connected to a fixed surface, kinesthetic feedback is not possible. Vibrational sensations can be implemented to convey information to the user.

2.4.2 Concept 2: EM tracked device

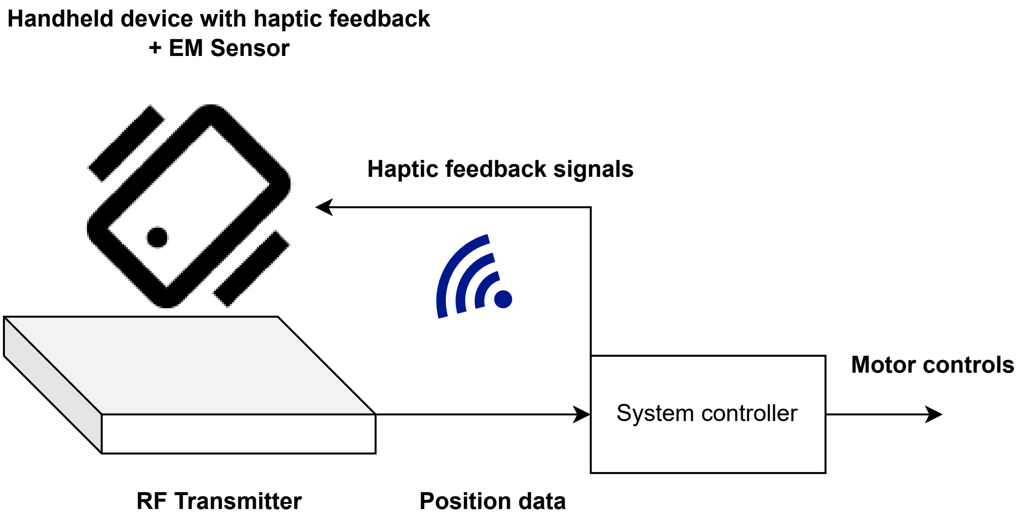


Figure 6: Second concept

The second concept is similar to the first but differs in its tracking method. With EM-tracking, the positional and rotational data can be tracked quite accurately. The workspace for this type of tracking method is lower but more accurate. It does have the same disadvantage as the previous concept, that no kinesthetic feedback can be implemented, which will suffer its realism score in the table.

2.4.3 Concept 3: Linkage tracked system with kinesthetic feedback

The last concept of the three utilizes a linkage-tracked system with kinesthetic feedback. By using encoders or other rotational sensors, the end position of the kinetic chain can be calculated. This tracking method can be relatively accurate and has several advantages. By connecting the links to a fixed surface, resistances and torques can be applied by adding motors / electromagnetic brakes to the joints. This way, kinesthetic feedback can be simulated. The idea of utilizing this combination is not new, so after the concept evaluation, a commercial system of this type is shown.

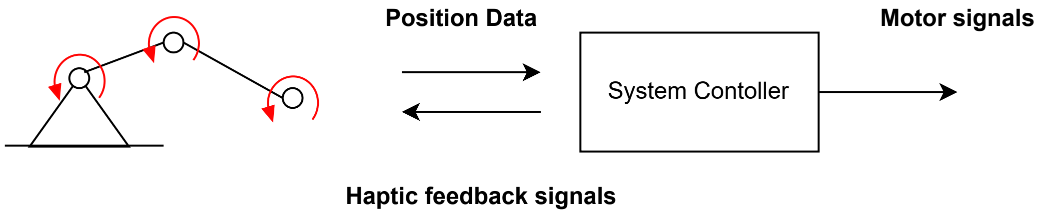


Figure 7: Third Concept

2.5 Concept evaluation

With all ideas bundled into three concepts, an analysis was done to determine which type of system would be the most suitable for this research. Assessing the feasibility of the concept ensures that it can be practically implemented within the timespan of this research. This factor can be considered a constraint for the research and thus is taken into account in this evaluation. Accuracy is crucial for the final system. If the system turned out to be inaccurate, the chance of mistakenly biopting different tissues becomes greater, defeating the purpose of the Sunram7 altogether. The goal of a haptic feedback controller is to simulate realism by haptically conveying information to the user. This criterium assesses if the system will be able to convey this information realistically. The usability of the controller is essential to ensure a positive experience with the device. Some concepts may require calibration and or maintenance to operate correctly. With this factor, procedures and requirements for calibrating the controller are considered. Range of motion refers to the extent in which the designed controller is able to move. Since this can be a limiting factor in some concepts, it is considered in the evaluation.

Each factor in the evaluation received a weighting factor to indicate its importance in the research. The factors of feasibility and accuracy, which are essential for creating a precise system, obtained the highest weighting factors. Additionally, since the usability of the system will be tested, it received a relatively higher weighting factor compared to the other factors. The weighting factor is multiplied by the number of points the concept gained for the evaluation. The total score is calculated by the sum of all the points multiplied by the respective weighting factor.

As shown in table 3, concept 3 scores the most points. It has high feasibility, relatively high accuracy, can simulate a realistic experience, and is easy to calibrate. One of the downsides of this system is the limited range of motion. Altogether, concept three obtained the most points and is thus chosen for this research.

Table 3: Concept evaluation score

	Weighting factor	Concept 1	Concept 2	Concept 3
Feasibility	4	3	4	5
Accuracy	4	3	5	4
Sense of realism	2	4	4	5
Ease of use	3	5	5	4
Calibration	2	2	3	5
Range of motion	2	5	2	2
Totaal aantal punten		61	69	72

2.6 Force Dimensions Omega.6

Since the design of the hardware turned out to be not feasible, research was conducted on commercial options to find an already existing solution. At the Robotics and Mechatronics group, Omega.x type systems were already in use. After looking up specifications of the different systems made by Force Dimensions, the Omega.6 turned out to be an excellent device for the purposes of this research. The Omega.6 has a pen-shaped end-effector, whose design allows for decoupling of translational and rotational movement.

Through the provided software development kit, the position of the device can be read in Cartesian coordinates. The device offers full gravity compensation and a driftless calibration procedure built-in. By applying torques on the three kinematic links, haptic feedback in all translational directions can be generated. The Omega.6 has a high refresh rate of up to 4kHz, which would, in theory, ensure the smooth operation of the controller. The workspace of this device is large enough, with a translational workspace of 160x110mm and rotations of up to 320 degrees in certain joints. The resolution claimed by Force Dimensions is less than 0.01 mm in all translational directions and 0.09 degrees in rotations. In translational movement, a force of up to 12N can be applied, which is sufficient for the purposes of this research[5]

Figure 8: Force Dimensions omega.6

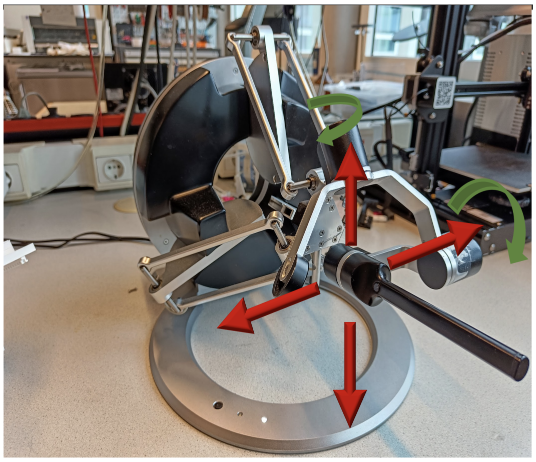
Given the availability of this device during the research period, it was selected for use.

3 Methods

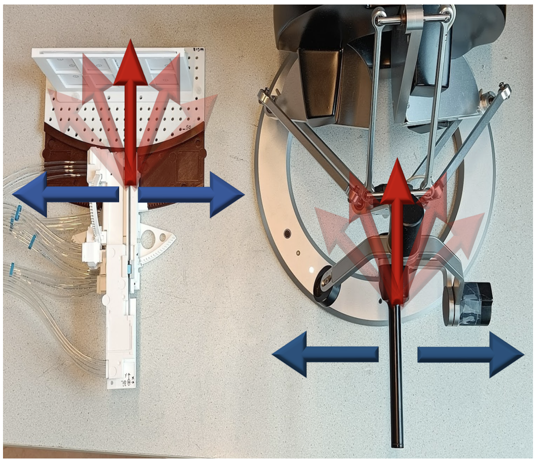
This chapter will describe how the system operates, and why the design choices for certain parts were made. After the general overview, some parts of the code are described more extensively.

3.1 Sunram7 Control

This paragraph illustrates the steering capabilities of the Sunram7 needle using the Omega.6 device. Following the bootup procedure, which is further explained in Chapter 3.4, the user can grasp the



(a) Control Inputs Omega.6



(b) Control Inputs Omega.6

Figure 9: Sunram7 control visualisation

pen-shaped end-effector of the Omega.6 and rotate or translate the pen. Consequently, the robot will replicate these movements, causing the needle to move accordingly. This direct correspondence between the user's actions and the resulting needle movement will hopefully result in an intuitive control method. Figure 9a shows all the possible translations and rotations. In Figure 9b, the direct correspondence of input and output is visualized.

3.2 General software overview

The general overview of the software structure is shown in figure 10. To start up the robot controller, the user will be prompted with a small UI interface in the command line. Here, the user can give the command to connect to the Sunram7 and choose to calibrate the omega.6. After pressing 's', the control system described in 10 will be activated.

First, the position and orientation of the omega.6 end-effector is measured and converted into usable data. With this data, a ray is constructed. This ray is used to calculate the necessary angles that the Sunram7 needs to make to put the needle approximately on the ray. To prevent damage to the robot, boundaries are implemented.

To go from the "Moving state" to the "Shooting state", the user can press the button on the omega.6. When this happens, all motors on the Sunram7 will be locked to prevent lateral movement while insertion of the needle. To start the haptic loop, a line segment over which the omega.6 can move is constructed. Once again, the current position of the end effector is measured, and this time in addition to the velocity. A vector from the current position to the defined segment is calculated and used for the force projection towards this segment. After this, the absolute distance from the coordinates of the omega when it entered the shooting state is converted to a Sunram7 command, to actually shoot the needle forwards.

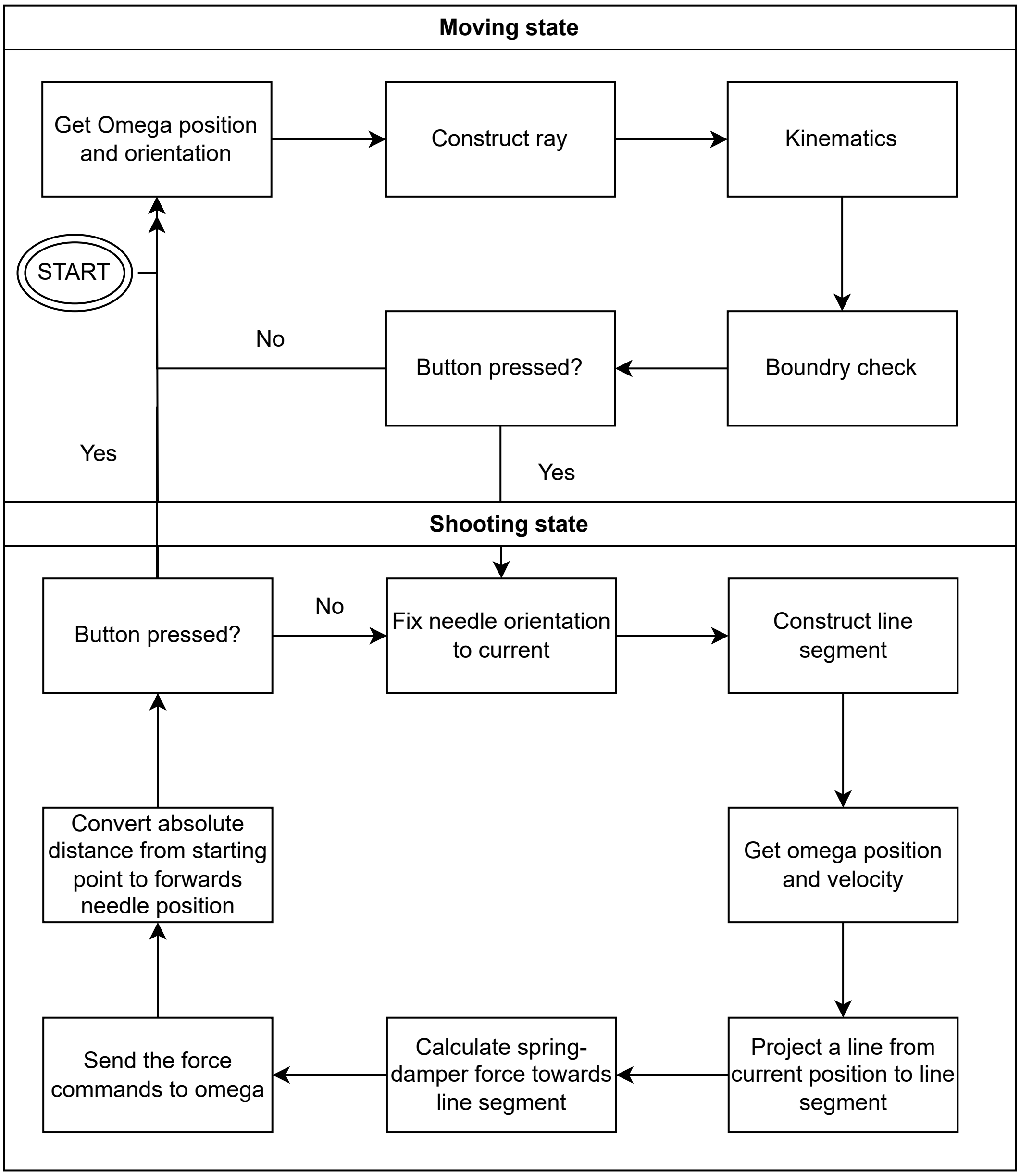


Figure 10: Codeflow overview

3.3 Class structure & States

The software is structured in three different Class structures. Each class has its own variables and functions to work with. This way, the variables are encapsulated within the domain that they need to work in. The first class, also visualized in Figure 11, is the Omega class. This class contains three accessible functions. Two of these are responsible for the boot-up procedure of the Omega.6 which will be further described in the next paragraph. The last function deals with projecting the haptic feedback on the user.

The controller, in code called main.cpp, is at the center of this code structure. Here, the inverse kinematics for steering the Sunram7 are calculated. The function kinematics() takes use of the other functions defined in this file. The Sunram Class only has two functions. The first is responsible for setting up and checking the serial connection through the USB port. If a command needs to be sent, the function sendCommandSunram() can be called from main.cpp. The string given within the brackets is then converted to a binary array and sent to the Sunram7 control board.

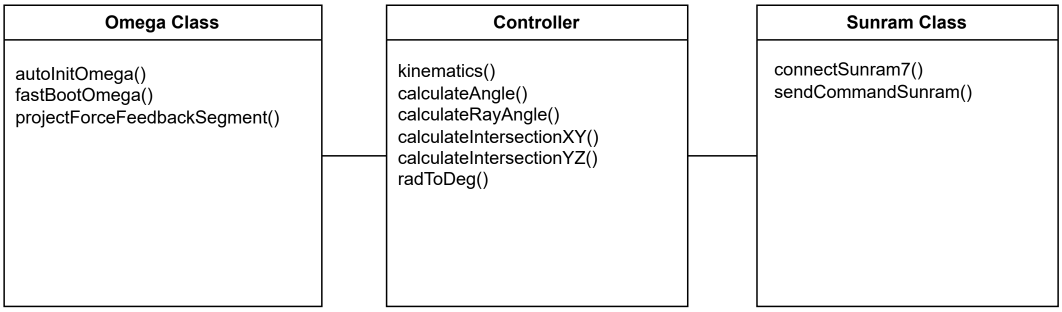


Figure 11: Class structure

3.4 Boot-up procedure

When compiled, an executable called "main" is created in the project folder. It does not need to be in the project folder to function properly. When opening the executable, a terminal window will open up. The user will be prompted with: "Launching Sunram7 Haptic Feedback Controller" to indicate that the software is booting up. The omega.6 has two separate boot up procedures. The first one, called by the function autoInitOmega() will calibrate all three motors and encoders to ensure the proper workings of the device. When finished, the pen-shaped end-effector moves to the central position. Sometimes, this is not necessary to do, for example when the device already has been calibrated on a previous run. To speed up things, a second boot option was included. The "fastBoot" option can therefore also be chosen by the user. Making a choice is done by entering Y for the autoInit bootup, F for the fastBoot and N for denying a bootup service.

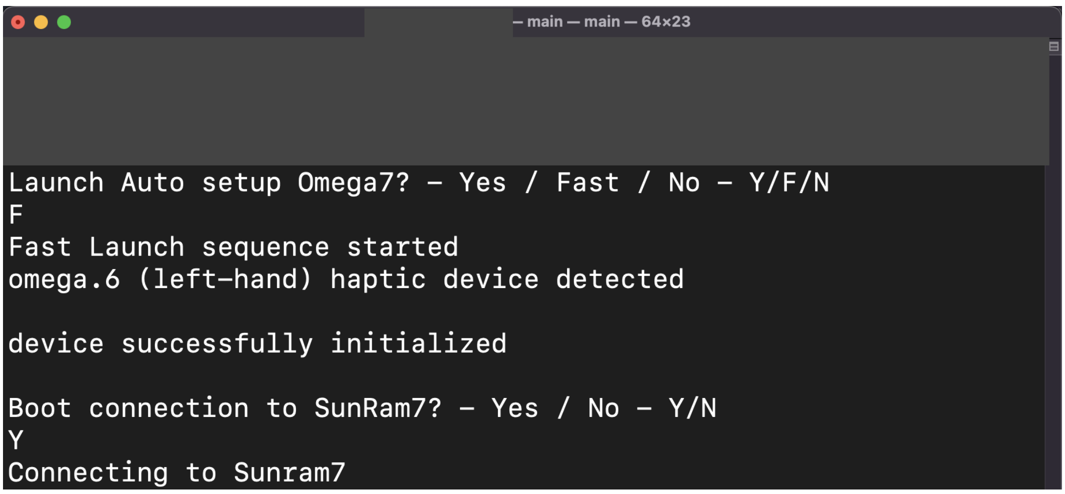


Figure 12: Boot-up terminal

If the omega.6 has successfully returned to the central position, it will return a success boolean to the main code. The user is informed about the status. Next up, a decision can be made if a connection has to be made with the Sunram7. As done before, either a Y or an N can be typed in the terminal.

After choosing an option, the system will start in the ”Standby” state. In this state, a command to the motors will be sent to ensure that every motor is in the home position, indicated by the markers on the robot itself. To start the movement of the robot, the letter ’s’, for ’start’ can be pressed on the keyboard. Now the system will read the input and start sending commands to the Sunram7 and the Omega.6.

As mentioned in the general code flow, the button on the omega.6’s pen can be used to let the robot move the needle forwards. This is when the projectForceFeedbackSegment() function is called to give the user haptic feedback. To exit this ’shooting’ state, the user can again press the omega.6 button. This will start a 4-second delay, in which the robot has time to retract the needle backward. This safety feature was implemented to ensure that no lateral or rotational movement can be made while shooting the needle and thus preventing damage to the tissue and robot.

When the entire operation needs to be stopped, the letter ’q’ can be pressed on the keyboard. This immediately stops all ongoing processes and no further movements can be made. The software will shut down and the terminal closes.

3.5 Inverse kinematics

In this paragraph, a description will be provided on how the signals from the omega.6 are converted into motor control signals that can be used by the Sunram7 control board. First, the function GetPositionAndRotation() from the Omega.6 is called. This returns the x, y, z coordinates and two angles of the end effector of the omega. The x,y,z coordinates are converted to a target vector, which will be called Target(T) in this report. All coordinates in T have been transposed so it is in the same coordinate system as the Sunram7. From T and the corresponding angles, a unit vector U is constructed. This is visible on the lower right of figure 13. By extending U, a ray becomes visible, indicated by the arrow. The main goal of the kinematic functions is to calculate the angles needed to position the needle of the Sunram7 at the location and orientation of the ray. Motor J1 moves along a semi-circular rail, so in this mathematical model, a circle can be constructed by the formula:

$$(x - x_c)^2 + (y - y_c)^2 = r^2 \tag{1}$$

With r being the radius of the circle, and x_c & y_c being the coordinates of the circle center. The position of J1 is determined by calculating the intersection of the ray with the circle.

Ray described by

$$\begin{pmatrix} R_x \\ R_y \end{pmatrix} = \begin{pmatrix} T_x \\ T_y \end{pmatrix} + \lambda * \begin{pmatrix} U_x \\ U_y \end{pmatrix} \tag{2}$$

In the formula R describes the ray, T the target coordinates gathered from the omega, λ can be of the subset $\mathbb{R}$ and U being the unit vector in the direction of the ray.

Substituting R_x and R_y into x and y respectively, a quadratic equation of the form:

$$A\lambda^2 + B\lambda + C = 0 \begin{cases} A = U_x^2 + U_y^2 \\ B = x_c \cdot U_x + U_x \cdot T_x - 2 \cdot y_c \cdot U_y + 2 \cdot U_y \cdot T_y \\ C = x_c^2 + T_x^2 - 2 \cdot x_c \cdot T_x + y_c^2 + T_y^2 - 2 \cdot y_c \cdot T_y - r^2 \end{cases} \tag{3}$$

By solving for λ, and substituting it into equation 2, either 0,1 or 2 solutions can be found. If no solutions are found, the robot cannot reach that ray. When one solution is found, the robot is exactly at the edge of its workspace. With two solutions, the ray crosses the circle two times. In this case, the intersection farthest in the negative Y direction is chosen, since the rail is also positioned in this direction. This coordinate, in addition to the center coordinates of the circle, are used to determine angle J1 with basic goniometric operations.

To actually align the needle with the ray, the difference in angles has to be compensated using motor 2.

$$J2 = \theta - J1 \tag{4}$$

In the technical documentation of the Sunram7 can be found how large the angle in/decreases per gear tooth. To find the command, the angle can be divided by this number, and rounded to the closest integer. The motors J3 and J4, responsible for the movement and angle in the Z direction, are calculated with the exact same method.

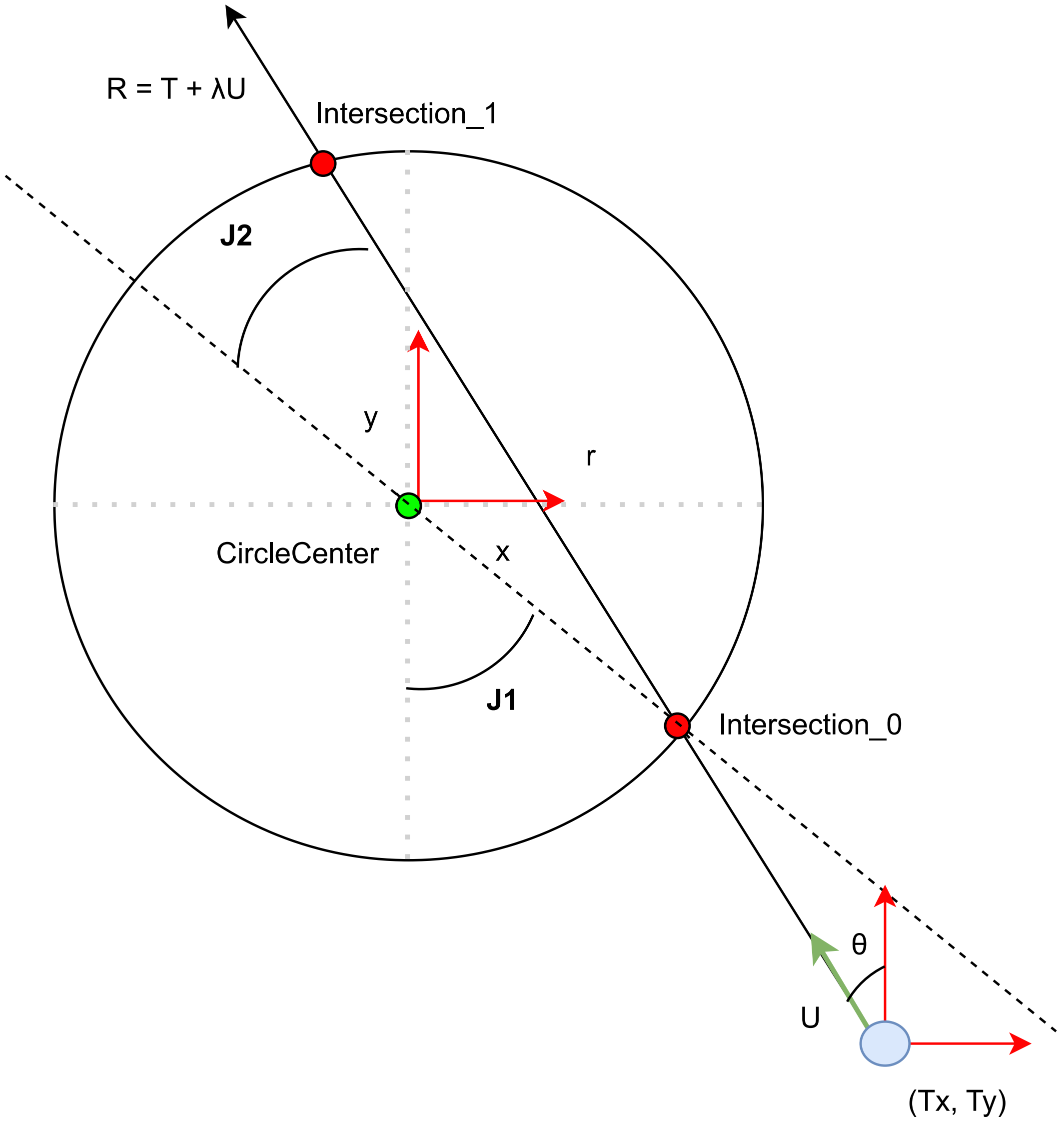


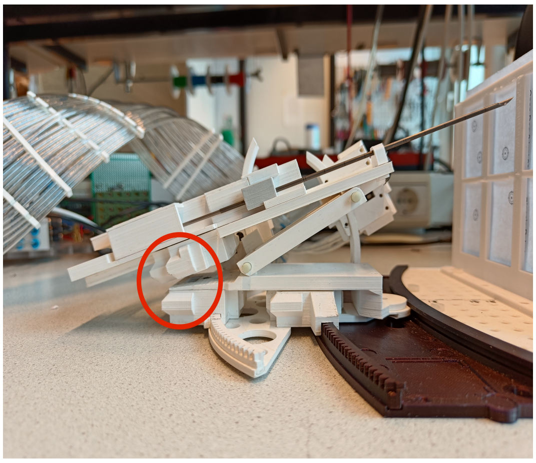
Figure 13: Kinematic model for the XY plane of the Sunram7. With a constructed ray starting at T, and in direction $U\lambda$. Intersections are determined from which angle J1 can be calculated. J2 derived from difference in θ & J1

3.6 Boundaries

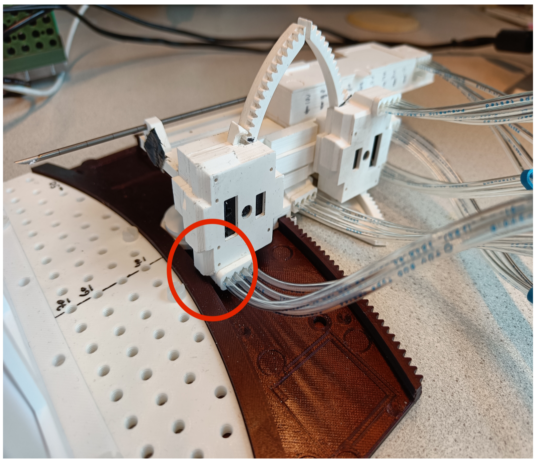
Due to a limited workspace, boundaries have to be implemented. Done for the protection of the parts and to prevent the robot from moving off the tracks. The Sunram7 has a few limitations in its workspace. First, measures have to be taken to ensure that the motors do not extend beyond the rails of the robot. This is done by defining a minimum and maximum value for the motor commands. If the calculated command is outside of the defined range, the closest possible value is sent to the robot.

In the YZ axis of the robot, as shown in Figure 14a, there is a risk of collision between two components. To mitigate this risk, the software restricts the movement of the motors responsible for this axis if one of the motors is not extended enough. This preventive measure ensures that the collision between the two parts is avoided.

If the needle is fully lowered, rotation within the XY plane can lead to a collision between motor J4, encircled in Figure 14b and the guide rail. To address this issue, a solution was made to restrict rotation when the needle is in the downward position, preventing damage.



(a) Back collision



(b) Front collision

Figure 14: Critical collision points of Sunram7

3.7 Haptic feedback

If the button, located at the pen of the Omega.6, is pressed, the needle can only move forwards in the direction it previously pointed at. As a result, the input controller can also only move in that direction. If the user pushes the controller off of this line segment, the machine will provide kinesthetic feedback to push the end effector back on the line. The next paragraph explains how the calculations for this feedback are done.

3.8 Segment calculation

For the haptic feedback, a virtual line between point A and point B, as demonstrated in Figure 15, is constructed within the Omega class. In every iteration, the projection from the current position is calculated to the line segment. Then, a guidance force is determined, modeled as a spring+damper system that pulls the device towards its projection on the constraint segment. The resulting force vector is applied to the Omega.6.

In the meantime, the absolute distance between A and the current position is calculated. This variable is used to determine how much the needle should extend forwards. This parameter is converted by dividing D by the step distance of the motor. Again, rounding this number leads to a motor command.

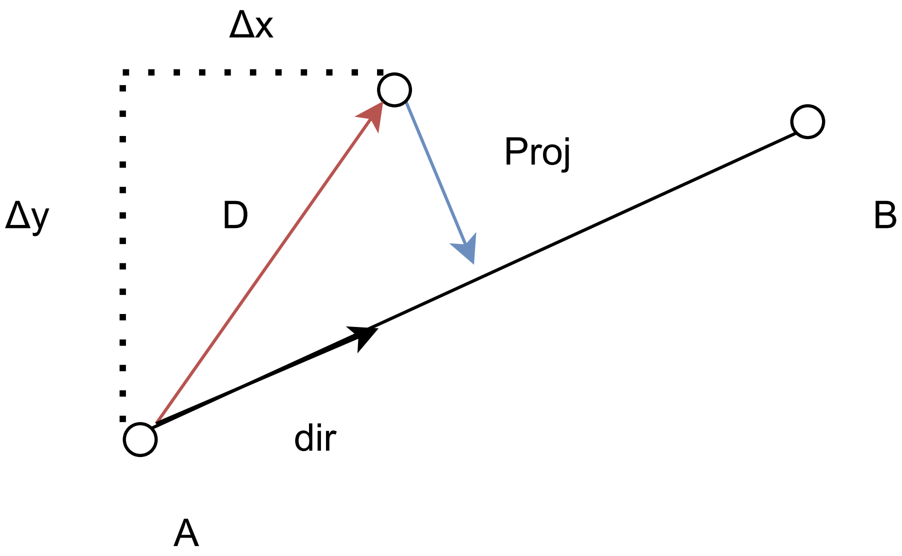


Figure 15: 2D representation of segment calculation

3.9 Hardware

To run the program, a MacBook Pro computer was used with a MACOS 12.6.3 operating system. The software for the UI is built entirely in an IDE, written in C++ and compiled using the Apple Clang version 14.0.0 compiler. The USB cable to the Sunram7 connects to the Programming port on the Arduino Duo responsible for controlling valves on the Sunram7 control board. This control board is shown in Figure 16.

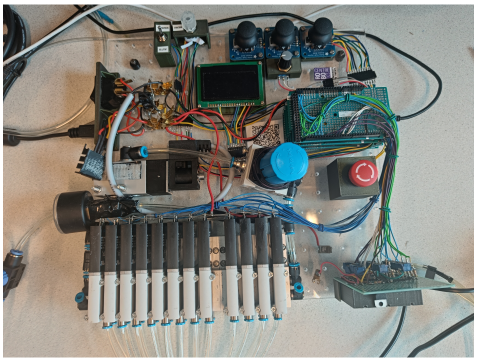


Figure 16: Sunram7 control board

4 Experimental approach

This chapter will describe how the different aspects of the designed system were tested. After describing the objective of every experiment, the conditions of every experiment are written down. This makes it possible to reproduce experiments in the future

4.1 Objective

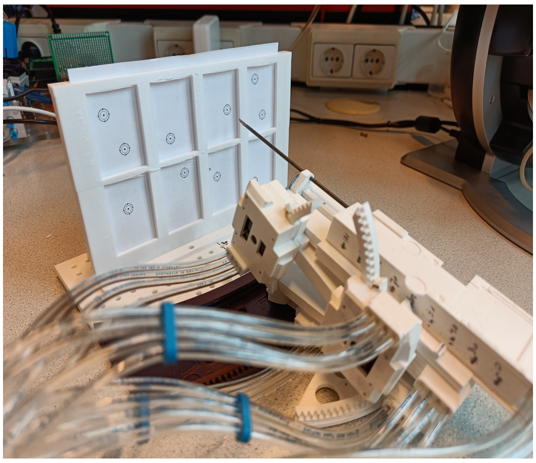
The first experiment gives an answer to the subquestion: What accuracy can be achieved by the user? After that is tested, the user is given a form to give an answer to the second subquestion: How is the usability of the system perceived by the user? Since previously built systems could be improved by decreasing delay[17], the last test checks the total system delay, answering the question: What is the total system delay?

4.2 Ethics review

Since user tests were conducted, an ethics review had to be done. Participants gave oral consent to participate in this research and were briefed beforehand. The data gathered in this research cannot be traced back to the participants and is fully anonymous.

4.3 Experimental setup

(a) Experimental setup



(b) Sunram7 with paper targets

Figure 17: Accuracy experiments setup

An experimental setup was constructed for the tests. As depicted in Figure 17a, the participant had the option to sit in an office chair equipped with armrests, providing support and preventing fatigue. On the table, positioned to the right side, the omega.6 device was placed. Depending on the dominant hand of the test subject, the device could also be positioned on the left side. The Sunram7 robot was placed on the table as well. To enhance the user's ability to aim the needle, the robot was raised slightly higher on the table by placing a case underneath it. Although not visible in this image, a laptop running the necessary software was present to control the system.

To simulate targets, papers were printed. These papers contained targets and reference markers. These are highlighted in Chapter 4.4 and shown in Figure 18.

4.4 Accuracy measurements

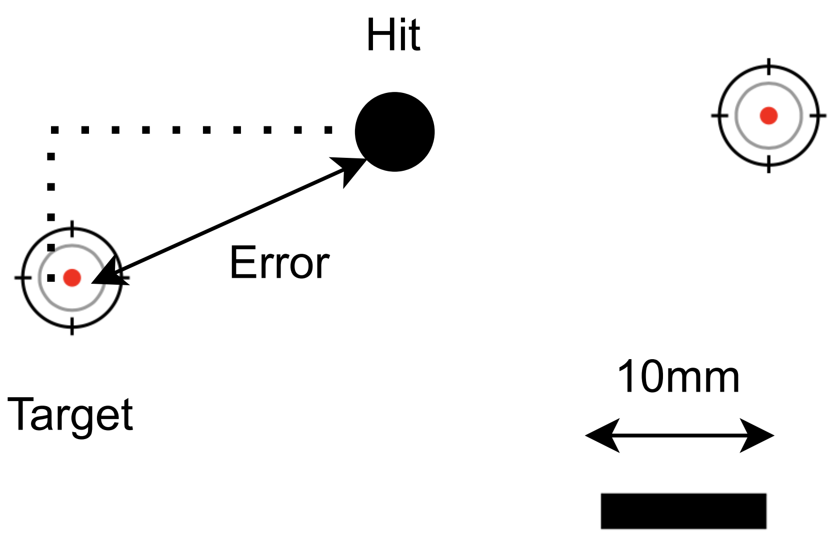


Figure 18: Accuracy Measurement

After a brief explanation of the goal of this test and an instruction on how to use the robot, the users were asked to poke a hole as close as possible to the target printed on a piece of paper. After hitting 3 targets, the paper was removed from the setup to store for later data analysis.

The paper targets were scanned and imported into a MATLAB program. Here, the distance between the desired target and the poked hole was measured. This was done by first calculating the pixel size of the image, by using the printed reference marker on the paper. The distance in pixels is then determined by manually clicking on the hole and the target. Conversion to mm was then done by multiplication with the previous factor. Human error can be introduced by misclicking the targets. This was minimized by zooming the image of the paper. Another limitation is is the pixel-size of the image. The scanner has a finite resolution, which will introduce an error in the measurements. Further error calculations will be shown in the results chapter of this article.

4.5 User Experience form

After participation in the controller test, users were asked to fill out a digital survey. The results were anonymously saved. In this survey, standardized SUS (System Usability Test) questions were used. Participants were able to rate their responses on a scale of 1 to 5, where 1 represented ”strongly disagree” and 5 represented ”strongly agree.” The following questions were asked:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.

5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

The SUS test was chosen because it is straightforward to administer to participants, can be used with a small number of participants, and has been proven effective in distinguishing between systems that are usable and those that are not [24].

4.6 Participants

Participants in this study were all Dutch-speaking students within the range of 18-26 years old. Participants enrolled in this study by responding to a digital invite.

4.7 Delay measurements

By installing a camera close to the previously mentioned setup, a delay measurement could be made. By giving the system an impulse on the input side, in this case, a fast movement to the Omega.6 end effector, the sunram7 would follow after a delay. By filming with a 240Hz camera , the number of frames could be counted between the movement of the input and output. With the known refresh rate, an estimate of the delay can be made by multiplying the number of frames by the time between each frame.

5 Results

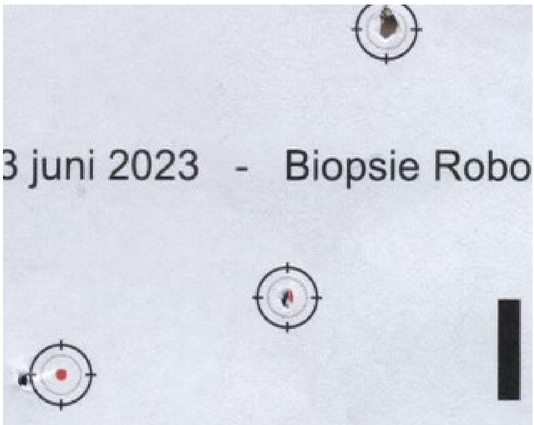
After the tests, the data of 10 participants could be gathered and analysed. This chapter will give an overview of the data gained by the user tests and delay tests.

5.1 Accuracy test

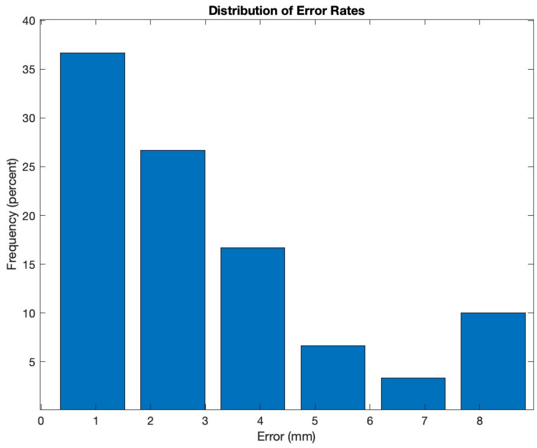
The paper targets were scanned and analyzed in MATLAB. To reduce the error in clicking the target and hitmarker, the scans were cropped, so MATLAB would view only the relevant areas. Figure 19a shows a cropped and zoomed target. While testing, it was noticed during the first test that some targets were more difficult to aim at than others. This was due to some boundaries that were set more strictly for the test. Since users do not know about the limitations of the robot, the decision was made to make the boundaries a bit more strict. This would ensure that the robot would absolutely not break during the tests. This is also why the users were instructed to only hit the middle three targets. On average, users were able to hit the target with an error of 3.09mm with a standard deviation of 2.46mm. Within the test, there was a large difference to be noticed in the results of the test subjects. The most accurate participant was able to hit three targets with an average error of 1.42mm, with two targets hit with an error of less than 1mm. The participant with the greatest error achieved a target error of 5,72mm on average.

During testing, one result was excluded from the research. The participant had a muscle disease, which influenced his performance. The participant was not able to reach the controller properly and had insufficient strength to acquire certain wrist angles. The results of this test were analyzed and came out to have an average error of 6,17mm.

During the testing, it was noticed that some users put in a lot of effort to line up and aim the needle. These users showed more interest in hitting the target accurately. On the other hand, some users were more focused on learning how to control the needle's movement and less concerned about hitting the target.



(a) Scanned and cropped accuracy data



(b) Accuracy test results

Figure 19: Accuracy experiment results

5.2 Usability test

The questions asked via Google Forms were exported to an Excel sheet, after which formulas could be added to analyze the data. Analysis is done according to the method developed by J. Brooke [2].

Calculation of a general score S is done by the formula:

$$P = Q_1 + Q_3 + Q_5 + Q_7 + Q_9 - 5 \tag{5}$$

$$N = 25 - (Q_2 + Q_4 + Q_5 + Q_8 + Q_{10}) \tag{6}$$

$$S = (N + P) \cdot 2.5 \tag{7}$$

Let Q_i denote the ith question. Let P represent the score obtained from positively asked questions, and N represent the score obtained from negatively asked questions. Among the 9 responses to the form, an average SUS score of 67.5 out of 100 was achieved, with a standard deviation of 11.46.

A standardized usability test is beneficial to compare it to other systems but does have some downsides. The first question was not perceived as relevant to the users. Since students will probably not be using this system, the question was a bit unnecessary.

5.3 Delay Test

Filming with a 240Hz camera, and counting the frames, the total system delay can be determined as 83.3 ms. Figure 21 shows a visual representation of the results. Based on user testing, the systems were perceived as highly responsive, with this reasonable delay.

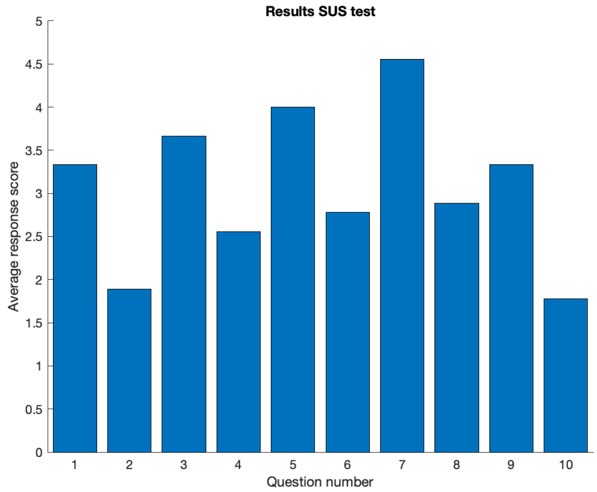
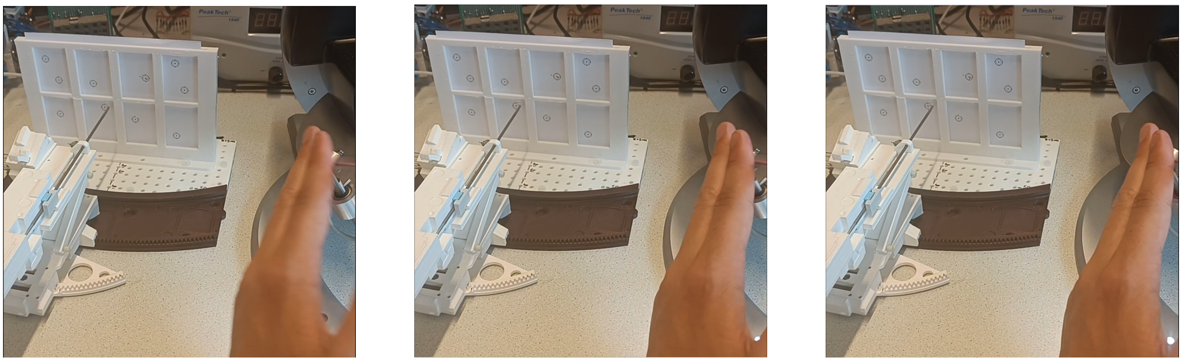


Figure 20: SUS test results



(a) t = 0, movement of input controller initiated

(b) t = 40ms, input controller moving. Sunram7 stationary

(c) t = 83ms, both input controller and Sunram7 moving

Figure 21: Delay measurement results

6 Discussion

This chapter discusses the results previously presented in Chapter 5. First, a reflection on the system design will be done, then an evaluation of the test methods is presented including important observations.

6.1 Requirement evaluation

In this research, a working prototype for a haptic feedback controller for the Sunram7 is made. This paragraph reflects on the systems according to the requirements set in Table 2. As of right now, the system cannot be properly used for MRI-breast biopsies. For this to happen, the system needs integration with the MRI images and software. Without this information, the surgeon would not know where to steer the needle to. The requirement of having an input controller is achieved, the Omega.6 is being used for this. This research did not look further into the ergonomics of this system, since an off-the-shelf input controller was chosen. Ergonomics are taken into account with the design of this device, so for this research, it was taken for granted. The user interface can provide haptic feedback to the user. A wish at the start of this research was to implement different haptic types for different tissue types. This was unfortunately not feasible to implement within the timespan of the production phase. A few safety features have been built in. The first safety barrier concerns the limits of the robot. The robot cannot go outside the defined boundaries, thus protecting the user and the robot itself. The emergency stop is prototyped using a key press 'q' on the laptop's keyboard. While shooting, certain degrees of freedom are disabled to ensure needle stability.

6.2 System evaluation

Although the system passes most requirements, flaws can be found and will be adressed in this paragraph. The first shortcoming of the built system is the compatibility across operating systems. The system is built on a MACOS operating system, so it will only work on a computer running this OS. Adjustments in the code can be made to accomplish cross-platform compatibility. For this, the main changes are within the connections with the Sunram7 and Omega.6. This incompatibility could cause issues if further research and development will be done on this system. In this research, no clear benefits or disadvantages are found using the MACOS operating system. Though more documentation and code examples are publicly available for Linux and Windows.

In the transformation from Omega coordinates to the coordinate system of the Sunram7. Some scaling factors are applied for better usability. If the target coordinates and angles were to be directly used, the system proved to be uncontrollable. Boundaries were reached quickly and the system was very sensitive. That's why the decision was made to scale certain parameters. In the software, the virtual target point T is moved by a pre-set amount, and the input angles are multiplied by a certain factor (< 1). As a result, the input controller becomes less sensitive, which makes it easier to use. This scaling allows for greater use of the Omega.6 workspace.

This improved the usability a lot. The downside of this approach is that the target coordinates do not correspond directly to the input anymore. The parameters that were used to tune the system can be tuned differently, and still produce a workable outcome. This comes down to personal preference.

As explained in chapter 3.5, the kinematics are determined by calculating the intersection of a ray with two (semi) circles. This calculation is flawed for the elevation commands. For this calculation, the assumption is made that the center of the circle does not move with respect to x and y. In reality, this is not the case. If the motors in the base plane move, the virtual rotation point of motors J3 and J4 moves too. This means that only in the home position, the needle is actually correct on the ray. Experiments showed that with this assumption, the system was still usable due to the relatively small translation of the virtual rotation points. To correct this error, the rotation point of J3 and J4 can be transformed into a coordinate system that accounts for the rotation of J1 and J2. In situations where no intersection can be found, such as when the controller is moved too high, the calculations yield imaginary results, rendering them incomprehensible. The code deals with this by returning to the home position. This has a very counterintuitive effect. When the user moves the controller too high, this safety feature will take effect and move the needle downwards. The user will try to compensate for this by moving the controller even further up. Users were notified of this phenomenon and were told when the controller was out of bounds to minimize the effect of this bug on the performance. Since the robot utilizes stepper motors, only movements in discrete steps can be made. This has an influence on the total accuracy. In the code, angles are rounded to the closest integer to get to a command as close as possible to the desired angle.

Due to the way the motors are designed, it is possible for a motor to skip one, or multiple teeth. Since the Sunram7 has no capabilities to sense this happening, the robot will drift and will become more inaccurate the more this happens. For this, several solutions have been found, for example in the research of Marijn Hilten. Adding camera tracking could possibly ensure that the robot maintains proper calibration [10].

Furthermore, as shown in Figure 15 the distance in which the needle will move forwards, depends on distance D. This distance is thus influenced by how much the user moves the controller away from the defined segment between A and B. This can give a counterintuitive result. In practice, this effect was not noticeable. This is probably due to the relatively small angle between the segment, and defined vector D. A better solution would be to use the projected point on the segment to determine a more accurate motor command.

6.3 Usability test

With the results from the form, a few conclusions can be made regarding system complexity, ease of use, integration of functions, consistency, and learnability. The system complexity was generally perceived as relatively simple, indicated by the average score of 2 on the question: ”I found the system unnecessarily complex”. The average score of the question ”I thought the system was easy to use” is 3.5. This can indicate that some users found the system easy to use, while others had to put in more effort to use the system. The score obtained by the question: ”I found the various functions in this system were well integrated” suggests that the system provides a cohesive experience in terms of integration of the different functions. Some things about learnability can be concluded with the results of questions: ”I needed to learn a lot of things before I could get going with this system” and ”I would imagine that most people would learn to use this system very quickly” These questions scored 1.6 and 4.7 respectively. This would imply that the users generally experience a low learning curve to start working with the system. The latter of the two results suggests that the user thinks that the system is easily learnable.

The subquestion: ”What accuracy can be achieved by the user?” can be answered with the results of the accuracy tests presented in the previous chapter. Users were able to hit the paper targets with an average error of 3.09mm. This accuracy test only measures the error in a 2D plane.

When comparing this to the median lesion size of 10mm, it appears that the system’s accuracy would be adequate for performing biopsies when aiming at the center of the lesion[12]. However, it’s important to note that this conclusion is based on accuracy determined in a 2D testing setup. Further research is needed to test if the same level of accuracy can be achieved in a 3D test. The developed system performed slightly inferior when compared to the system discussed in the state-of-the-art analysis. However, a direct one-to-one comparison between the two systems is not possible due to the use of different testing methods. To establish a fair comparison, it would be appropriate to replicate the experiment described in the paper.

6.4 Test evaluation

In this paragraph, an evaluation of the test methods will be done. Regarding the accuracy test, several aspects can be discussed regarding the validity of the test. In the current setup, users were required to visually aim by observing the needle path on the robot. Consequently, the ability to predict where the needle would end up becomes a factor of influence. This was observed during the initial test, and measures were taken to minimize its influence. However, the complete elimination of this factor cannot be guaranteed. To determine how much impact this had on the results, another test could be set up wherein users can evaluate the haptic controller in a virtual environment. This controlled environment would enable testing of users' skills with the haptic controller while eliminating the aiming factor.

As mentioned in Chapter 5.1, there was a noticeable difference in how users behaved. Although this experiment wasn't meant to test their attitudes toward the new technology, it might have influenced the results. To get a clearer answer, more testing and research could be done. Focusing more on hitting the targets accurately in future studies would be a good idea. Further testing could help determine if this approach is practical.

Although a SUS test can give a clear indication of the usability of the system, the results may give the wrong impression for several reasons. The first is the lack of expertise. The students performing the test had no prior knowledge of robotic surgery, or performing any health-related procedures. In addition, the students were all students of a technical university and may be biased towards technical proficiency. This bias may shift the focus of the evaluation. While the technical aspects of the controller were important, the requirements and criteria for an experienced surgeon may have been different. Therefore, it would probably be more appropriate to also include healthcare professionals in the testing phase of the system.

The total delay in the delay test is influenced by several factors. First, the transmission delay from the omega to the laptop. Secondly, there is the time required to calculate the kinematics and send out the signals to the Sunram7 control board. Additionally, the valve needs to actuate, and air needs to flow. The inertia of the robot also contributes to the overall delay. Furthermore, the motor operates in discrete steps, and the rounding of values during motor operation adds to the delay and introduces errors. The results of the delay test can only be interpreted as the total system delay. Further testing could point out how much delay the software introduces. With a relatively low delay of 83 ms, the system was perceived as fast and responsive.

7 Conclusion

In conclusion, the developed software, in combination with the omega.6, shows potential for creating a Sunram7 haptic controller. With the addition of the appropriate safety features, the system can possibly provide a reliable and accurate interface, but further testing is required to ensure its effectiveness.

To ensure safety, relevant features such as collision prevention and disabling certain motors have been included to halt the robot in a safe manner, thus minimizing the risk of damage and harm to the users. Nevertheless, rigorous testing and verification are necessary to validate the system's safety performance.

Information about the needle path is conveyed to the user with the help of the Omega.6. Regarding performance, the achievable accuracy mainly depends on the user. On average, users were able to hit targets with an error of 3.09 mm.

The usability of the system was a crucial aspect of this research. By conducting user studies, the conclusion can be made that the system was perceived well by the user, with an average usability score of 6.75. However, it is important to note that this finding is solely based on quantitative results. Further assesment can be done to get more comprehensive feedback about the systems' usability.

In summary, while the initial findings have shown that software for a haptic feedback controller for the Sunram7 can be made, more research is needed to validate the safety of the system, accuracy in real-world scenarios, and usability.

7.1 Recommendations

Currently, the user has the ability to visually guide the needle towards the target. However, in an MRI environment, this approach is not feasible. There are two main reasons for this. Firstly, due to the strong magnetic field, it is not possible for the Omega.6 controller to be present in the same room as the robot. Secondly, since the targeted lesions are not visible to the naked eye, the surgeon lacks the information necessary to accurately aim at the lesion. To address this challenge, establishing a connection between the Computer-Assisted Diagnosis System could serve as a potential solution, enabling the user to precisely target the lesion despite the limitations of the MRI environment.

The current prototype only includes haptic feedback related to the needle path. However, considering the capabilities of the omega.6 controller, there are several other potential solutions to convey information to the surgeon. For instance, the depth of the lesion is currently not perceptible to the user. Providing feedback when the target is reached in terms of depth could possibly benefit the surgeon. Furthermore, the prototype currently lacks collision detection with the skin. By adding this feature, an additional layer of safety can be given as it would be able to prevent unintended needle insertion.

As mentioned earlier, there is currently no method to verify whether the Sunram7 is positioned and oriented as commanded. The skipping of gearteeth can significantly affect the needle's position. However, it is worth noting that camera tracking capabilities have been developed for the Sunram7, which, if added, could potentially enhance the system's reliability.

References

[1] Anastasia Antoniou et al. "Phantom-based assessment of motion and needle targeting accuracy of robotic devices for magnetic resonance imaging-guided needle biopsy". In: *The International Journal of Medical Robotics and Computer Assisted Surgery* (May 2023). ISSN: 1478-5951. DOI: 10.1002/rcs.2526.

[2] John Brooke. "SUS: A quick and dirty usability scale". In: *Usability Eval. Ind.* 189 (June 1995).

[3] Marie-Claude Chevrier et al. "Breast Biopsies Under Magnetic Resonance Imaging Guidance: Challenges of an Essential but Imperfect Technique". In: *Current Problems in Diagnostic Radiology* 45.3 (May 2016), pp. 193–204. ISSN: 03630188. DOI: 10.1067/j.cpradiol.2015.07.002.

[4] Marianna J. Coulentianos et al. "Stakeholders, Prototypes, and Settings of Front-End Medical Device Design Activities". In: *Journal of Medical Devices, Transactions of the ASME* 16.3 (Sept. 2022). ISSN: 1932619X. DOI: 10.1115/1.4054207/1139853. URL: https://asmedigitalcollection.asme.org/medicaldevices/article/16/3/031010/1139853/Stakeholders-Prototypes-and-Settings-of-Front-End.

[5] Force Dimension. *Haptic Devices*. 2023. URL: https://www.forcedimension.com/products/omega.

[6] Alfred M. Franz et al. "Electromagnetic Tracking in Medicine—A Review of Technology, Validation, and Applications". In: *IEEE Transactions on Medical Imaging* 33.8 (Aug. 2014), pp. 1702–1725. ISSN: 0278-0062. DOI: 10.1109/TMI.2014.2321777.

[7] Samuel Frishman et al. "Enabling In-Bore MRI-Guided Biopsies With Force Feedback". In: *IEEE Transactions on Haptics* 13.1 (2020), pp. 159–166. DOI: 10.1109/TOH.2020.2967375.

[8] Peng Gao et al. "Recent Progress for the Techniques of MRI-Guided Breast Interventions and their applications on Surgical Strategy". In: *Journal of Cancer* 11.16 (2020), pp. 4671–4682. ISSN: 1837-9664. DOI: 10.7150/jca.46329.

[9] V. Groenhuis. "Robotic systems for breast biopsy using MRI and ultrasound imaging". PhD thesis. Enschede, The Netherlands: University of Twente, Jan. 2020. ISBN: 9789036548922. DOI: 10.3990/1.9789036548922.

[10] Marijn van Hilten. "Calibration and Open-Loop Control of Sunram7L: an MR Safe Robotic System for Breast Biopsy". PhD thesis. Enschede: University of Twente, 2022.

[11] HOLOGIC. *ATEC® Breast Biopsy System*. URL: https://hologicvirtual.com/product/atec-breast-biopsy-system-for-stereotactic-biopsy.

[12] Laura Liberman et al. "Does Size Matter? Positive Predictive Value of MRI-Detected Breast Lesions as a Function of Lesion Size". In: *American Journal of Roentgenology* 186.2 (Feb. 2006), pp. 426–430. ISSN: 0361-803X. DOI: 10.2214/AJR.04.1707.

[13] Soo Chul Lim, Hyung Kew Lee, and Joonah Park. “Role of combined tactile and kinesthetic feedback in minimally invasive surgery”. In: *The International Journal of Medical Robotics and Computer Assisted Surgery* 11.3 (Sept. 2015), pp. 360–374. ISSN: 1478-596X. DOI: 10.1002/RCS.1625. URL: https://onlinelibrary.wiley.com/doi/full/10.1002/rcs.1625%20https://onlinelibrary.wiley.com/doi/abs/10.1002/rcs.1625%20https://onlinelibrary.wiley.com/doi/10.1002/rcs.1625.

[14] Metropolitian Hospital. *Breast*. URL: https://www.metropolitan-hospital.gr/en/services/innovative-services/radiology-medical-imaging/our-services/breast#mri-guided-biopsy.

[15] Sue M Moss et al. “Eff ect of mammographic screening from age 40 years on breast cancer mortality in the UK Age trial at 17 years’ follow-up: a randomised controlled trial”. In: *Lancet Oncology* 16 (2015), pp. 1123–1132. DOI: 10.1016/S1470-2045(15)00128-X. URL: www.thelancet.com/oncology.

[16] NORAS MRI products. *Biopsy Unit for BI 320*. URL: https://www.noras.de/en/mri-accessories/biopsy-units/bu-for-noras-bi-320/.

[17] I.H.J. Ooijevaar. *Design of a User-friendly Controller for the Sunram 7 with Safety Features to Assist Radiologists in MRI-guided Breast Biopsy*. Tech. rep. Enschede: Robotics and Mechatronics, Nov. 2022.

[18] Oxford Languages. *Defintion of Haptics*.

[19] Claudio Pacchierotti, Domenico Prattichizzo, and Katherine J. Kuchenbecker. “Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery”. In: *IEEE Transactions on Biomedical Engineering* 63.2 (Feb. 2016), pp. 278–287. ISSN: 15582531. DOI: 10.1109/TBME.2015.2455932.

[20] Issam El Rassi and Jean-Michel El Rassi. “A review of haptic feedback in tele-operated robotic surgery”. In: *Journal of Medical Engineering & Technology* 44.5 (2020), pp. 247–254. DOI: 10.1080/03091902.2020.1772391. URL: https://doi.org/10.1080/03091902.2020.1772391.

[21] Jessica Schulz et al. “An embedded optical tracking system for motion-corrected magnetic resonance imaging at 7T”. In: *Magnetic Resonance Materials in Physics, Biology and Medicine* 25.6 (Dec. 2012), pp. 443–453. ISSN: 0968-5243. DOI: 10.1007/s10334-012-0320-0.

[22] Françoise J. Siepel et al. “Needle and Biopsy Robots: a Review”. In: *Current Robotics Reports* 2.1 (Jan. 2021), pp. 73–84. ISSN: 2662-4087. DOI: 10.1007/s43154-020-00042-1.

[23] Angela Sorriento et al. “Optical and Electromagnetic Tracking Systems for Biomedical Applications: A Critical Review on Potentialities and Limitations”. In: *IEEE Reviews in Biomedical Engineering* 13 (2020), pp. 212–232. ISSN: 19411189. DOI: 10.1109/RBME.2019.2939091.

[24] U.S. General Service Administration. *System Usability Scale (SUS)*. URL: https://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html.

[25] University College London. *Electromagnetic tracking*. URL: https://mphy0026.readthedocs.io/en/latest/tracking/em.html.

[26] *Worldwide cancer data — World Cancer Research Fund International*. URL: https://www.wcrf.org/cancer-trends/worldwide-cancer-data/.