

A positioning sensor device for biomedical robot : development and application to a laser skin stimulator

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Abstract

Since the dawn of time, humans have tried to reduce pain by various means and to understand its origin. Today, tremendous advances in science and technology have shown that pain is not a simple concept. In most of the cases, minor pain can be treated or eased by a physiotherapist or by using different kinds of drugs. However, more complex feelings like chronic pain are difficult to treat. Studying how the nervous system of humans work and how the brain interprets the pain signals is still a challenge.

Among the people working for the Institute of NeuroSciences (IoNS) of the Université catholique de Louvain (UCL) , the neurologist and professor André Mouraux carries out research on pain. To perform his experiments, he is currently using a laser stimulator to briefly heat the hand or foot dorsum so that the person feels a minor pain. This information is sent to the brain thanks to sensors sensitive to pain (nociceptors) through the peripheral nervous system. In some experiments, this operation is repeated approximately 40 times.

The goal is to obtain constant stimuli as much as possible. Therefore, before every stimulation, the laser must be positioned precisely with respect to the skin surface : at a distance varying from 85 mm to 115 mm and perpendicular to it with a maximal error of 15° . Since the experiment is tedious and tiring, André Mouraux is looking for a system allowing to hold and correctly position the laser with respect to the skin. The list of specifications expresses that two separated devices are needed to fulfill the whole need. On the one hand, a robot must hold and move the laser in space. On the other hand, a sensing device needs to give information about the skin surface. This information is then sent to the robot as a movement to place the laser correctly compared to the skin. This master thesis is precisely dedicated to this sensing device. The objective is to design, build and test such a system.

Firstly, information about points belonging to the skin surface needs to be known. For this purpose, two technologies are identified : 3D scanners and distance sensors. A state of the art of existing technologies is presented. From these researches, the technologies are discussed and two possible solutions are chosen : a 3D scanner using structured light technology and a system composed of three distance sensors using laser triangulation. Since neither of these methods can be differentiated on paper, they are implemented and compared based on predefined criteria. An experimental protocol is followed with the help of an industrial robot to hold and position precisely both systems in space. It allows to come to the conclusion that both methods fulfill the requirements. On the one hand, the 3D scanner is accurate since the maximal angular error observed is of 6° . However, it is not able to take into account possible movements of the subject. If the patient moves, a new scan taking approximately 75 seconds is necessary to update the scene. On the other hand, the system with three distance sensors is less accurate since the angular error sometimes exceed the 15° limit. Nevertheless, it happens in a few complex situations. Its main advantage is that it is able to update its measurements 5 times per second making it capable of taking into account the possible patient movement.

Finally, conclusions are drawn on the work performed during this final year and possible ways of improvements are proposed for a potential subsequent work.

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List of abbreviations

3D	Three-Dimensional
ADC	Analog to Digital Converter
ALS	Ambient Light Sensor
CIDE	Cerebellum Integrated Development Environment
CR	Constraint requirement
DOF	Degree of Freedom
FR	Functional Requirement
GPIO	General Purpose Input/Output
I2C	Inter-Integrated Circuit
IoNS	Institute of NeuroScience
IR	Infra-Red
IREDD	Infra-Red Emitting Diode
OBJ	Objet 3D
PLY	Polygon File Format or the Stanford Triangle Format
PSD	Position Sensitive Detector
STL	STereoLithography
UCL	Université catholique de Louvain
USB	Universal Serial Bus

List of symbols

α	Angular error on the system induced by ϵ	[°]
ϵ	Measurement error of the distance sensor	[mm]
$\mathbf{n}$	Normal of the approximated skin plane	

$\mathbf{o}^{12}$	Vector linking O^1 to O^2	
$\mathbf{o}^{13}$	Vector linking O^1 to O^3	
$\hat{\mathbf{l}}_{\text{laser}}$	Frame of the laser head	
Π	Equation of the approximated skin plane	
$\mathbf{v}^i$	Distance sensors line emission direction of the i -th sensor expressed in the laser head frame	
$\hat{\mathbf{l}}_{\text{robot}}$	Frame of the robot VIPER s650	
$\hat{\mathbf{l}}_{\text{Sense}}$	Frame of the SENSE [®] 3D scanner	
θ_h	SENSE horizontal field of view	[°]
θ_v	SENSE vertical field of view	[°]
a, b	Linear approximation parameters of the relation given by the SHARP datasheet	
D	Diameter of the circle formed by the origin of the three distance sensors line emission	[mm]
d^i	Distance sensors measurement of the i -th sensor	[mm]
D_{Sense}	Distance of the SENSE 3D scanner compared to the table	[mm]
h	Height of a skin irregularity	[mm]
L_{min}	Minimum length to be scanned by the 3D scanner	[mm]
n_1	V_1 number of occurrences	
n_2	V_2 number of occurrences	
O^C	Coordinates of the point targeted by the laser head	
O^F	Coordinates of the laser head origin	
O^i	Position of a i -th point belonging to the skin surface	
P^i	Position of the origin of the i -th distance sensor line emission expressed in the laser head frame	
V_1, V_2	Two most appearing values among 100 measurements in the SHARP raw data	
v_{sound}	Speed of sound	[340 m/s]
W_{min}	Minimum width to be scanned by the 3D scanner	[mm]

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This master thesis introduction outlines the context of the work, the problematic encountered by a person in the medical field, the objective pursued to solve its issue and finally exposes the structure of the work done during this year to reach this objective.

Context

Neurology is the branch of medicine concerned with the study and treatment of disorders of the nervous system. This complex system is composed of two major parts : the central nervous system (brain and spinal cord) and the peripheral nervous system reaching the eyes, the skin and almost everything in our body. The study of the nervous system is related to the field of neuroscience. The domain of applications is very large. Over the last fifteen years, advances in neuroimaging have led to extraordinary advances in neuroscience : scientists can now obtain images of the brain in activity that can improve the diagnosis and the treatment of neurological or psychiatric diseases. Although having made great progress in recent decades, there are still challenges. The biggest challenge remaining is to link biology (neurons) to psychology such as consciousness, mind, intelligence, perception of pain etc.

Pain is precisely the specialty of the algology laboratory of the Institute of NeuroScience (IoNS) . Algology is a branch of neuroscience whose purpose is to study pain and its effects on the body. This laboratory is part of the Université catholique de Louvain (UCL). Its research activity aims at a better understanding of the physiology and pathophysiology of pain in human bodies. The ability to perceive pain is crucial for survival, but pain is also a major healthcare issue as its treatment constitutes a very problematic challenge. Chronic pain affects the quality of life of millions of individuals, and imposes a severe financial burden upon our societies. Therefore, progress in understanding the neural representation of pain in humans is not only important for basic neuroscience research. Indeed, it is also critical to develop effective strategies for the diagnosis and management of pathological pain conditions [1].

André Mouraux is currently working at the IoNS and is also a professor at the UCL. He is using a CO₂ laser stimulator to briefly heat the skin. Under the skin, the nervous system is composed of numerous endings detecting external signals and transmitting them directly to the brain. The interest of stimulating the skin is to study the brain responses evoked by the activation of pain receptors called *nociceptors*. The final objective is to see how the human brain processes nociceptive sensory input and how this leads to the perception of pain. Possible applications of these studies are various. For example, it is a diagnostic tool to analyze the nervous system and see potential neuronal failure. It can also be used for fundamental research to gain a better understanding of the nervous system.

The laser stimulation system used to heat the skin is illustrated in Figure 1. It comprises a head mounted at the end of an optical fiber of several meters, in which the laser beam flows.



Figure 1: General view of the complete stimulation system

To study the behavior of these nociceptors, the choice of using a laser is justified by the fact that the skin must not be touched while stimulated. Otherwise, mechanical receptors or *mechano-receptors*, represented in Figure 2, would also be activated leading to a polluted brain response. The laser allows to stimulate the nociceptors repeatedly using heat in a very specific area while being non-invasive.

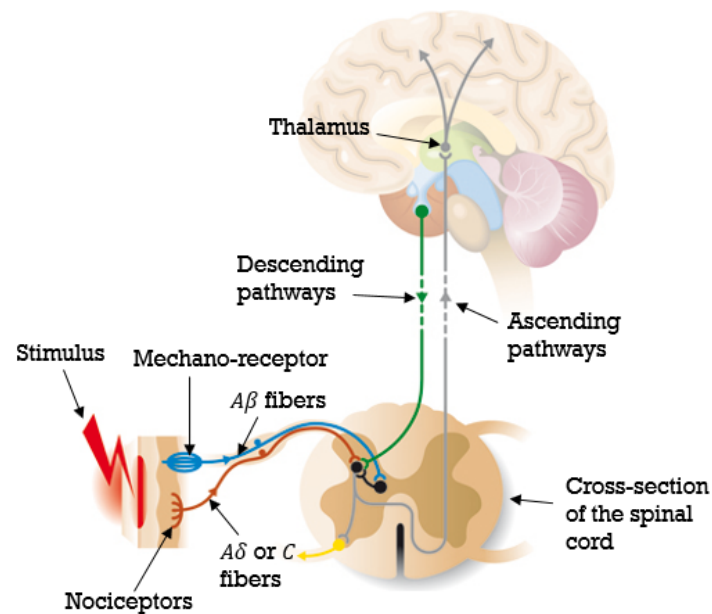


Figure 2: Simplified illustration of the nervous system when stimulating the human skin [2]

The laser power is regulated using a feedback control based on a real time measurement of

skin temperature at the site of stimulation. Nociceptors in Figure 2 are divided in two main categories: the $A\delta$ and C fibers. Both are responsible of pain feelings and are sensitive to pain. However, their threshold and response times are different. By knowing precisely the temperature at the skin surface, it is possible to know exactly which fiber is activated [3].

In practice, to perform a complete experiment, the laser pulses are repeated about 40 times. After each stimulation, the aimed target is slightly shifted from the previous location as depicted in Figure 3. The goal is to avoid problems related to excessive heating of the skin, or sensitization of the nociceptors. The pain thresholds of the nociceptors change after being stimulated. It leads to different brain responses whereas the stimuli must be the same to produce interesting data. The neurologist must therefore wait a given time (1 or 2 minutes) before stimulating again at the same location.

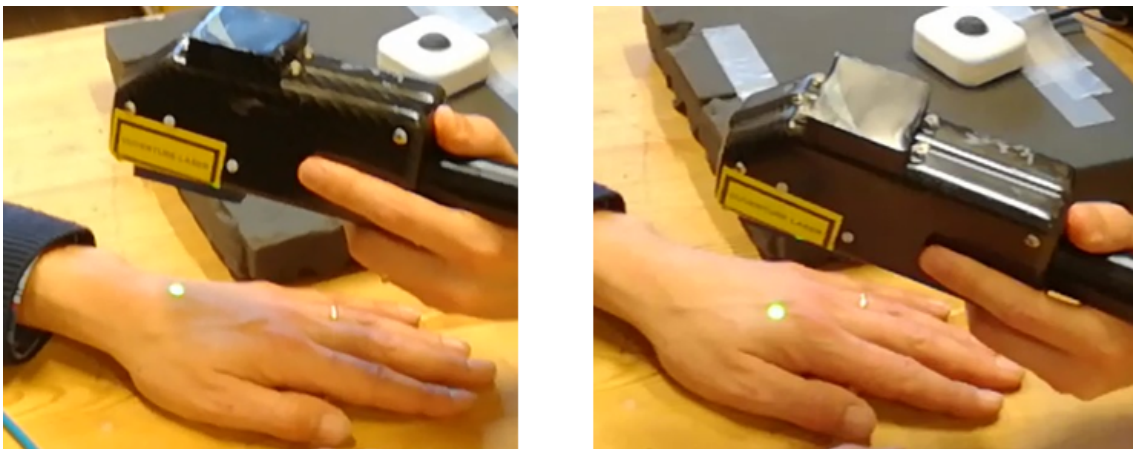


Figure 3: Stimulation process : the next stimulation area is different than the previous one

The zones of stimulation of these studies are illustrated in green in Figure 4. It consists of the back of the hand (hand dorsum) or of the foot (foot dorsum). Both hands or feet can be stimulated during the same experiment. In this particular case, a stimulation is performed on one hand or foot and then the same one is performed on the other to see if the patient reacts identically.



Figure 4: Stimulation areas for the experiments : hand and foot dorsum

Problematic

At the moment, the experiments are performed with the laser head held in hand by the neurologist or fixed to an external solid structure. This leads to a long and tedious work since, for every new stimulation, the structure must be adapted to correctly place the laser. Moreover, it is a source of inaccuracy as regards the stimuli. Indeed, the stimuli depend on the orientation of the laser beam compared to the skin. This principle is illustrated in Figure 5.

By vibrating the optic fiber at some distance from the source, a quasi-uniform spatial distribution of radiative power within the stimulated area is obtained [1]. The laser beam has a circular section with a diameter of 6 mm. If the laser beam is not perpendicular to the targeted surface, the stimulated area is wider. Therefore, the power density transmitted to the skin is lower inducing a smaller increase of the skin temperature.

To overcome this issue, the laser contains a controller measuring this temperature and adapting the power sent accordingly [3]. It means that if the laser beam is not perfectly perpendicular, the laser will detect that the temperature is too low and will increase the power to reach the desired temperature. However, the power of the laser is limited such that the maximum error allowed is 15° from the vertical in any direction.

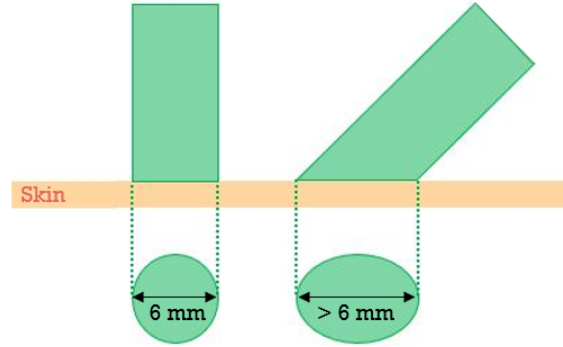


Figure 5: Influence of the tilting angle concerning the power distribution

Another issue is the fact that the skin is composed of irregularities such as veins or tendons. If the neurologist aims an irregularity with the laser beam, the power distribution on the skin circular area is not uniform. As illustrated in Figure 6, the top part of the irregularity is hotter than the sides for the same reason as before. The three zones covered by the laser beam have the same width but the skin surface is wider for the sides. It induces again a lower power density and therefore a smaller temperature increase on the lateral sides. For this reason, the neurologist avoids stimulating fingers and thick irregularities.

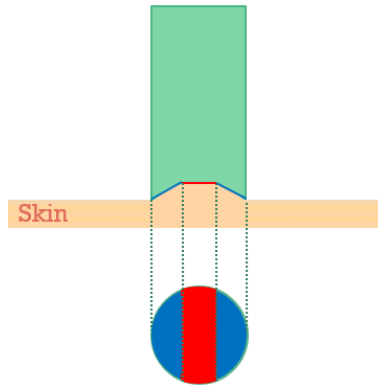


Figure 6: Influence of a skin irregularity concerning the power distribution

The laser head is also equipped with a distance sensor to know the distance separating the laser head from the target. The distance between the laser head and the skin does not affect the power density if it stays in the range between 85 mm and 115 mm from the skin. Inside this range, the laser beam section is approximately constant. Outside this range, the section size changes in a significant way inducing an important change in power density for the same reason as explained before. If this variation is too high, the temperature regulation becomes impossible. In addition, outside this distance range, the temperature measurement is not one hundred percent reliable. This is the reason why the laser disarms itself if the neurologist moves the laser head out of the 85-115 mm range. Indeed, it prevents accidental laser shots. It is therefore important to stay in this range at the moment of stimulation to avoid increasing the experiment duration.

Objective

Last year, this problematic was already tackled in the context of the course *LMECA2355 - Mechanical design in Biomedical Engineering*. It allowed to make a first study of the subject, to establish a first list of specifications and to propose some ideas. Moreover, André Mouraux guided us more easily regarding his expectations during the first meeting.

The objective of this master thesis is to design and test a measuring system which evaluates two quantities : the distance from the target as well as the angle between the laser beam and the normal of the targeted surface. It must provide an adjustment to position the laser head in the correct pose (position and orientation). This measuring system can then be embedded on a structure or a robot to adjust the laser pose automatically. Our goal is to design a solution based on existing technologies and not starting from scratch : take benefit from current technologies to meet a new need.

Structure of the work

This master thesis is subdivided in three main parts :

1. The first part is dedicated to the sensing device design. It begins with the list of specifications in order to clarify the needs of André Mouraux. Then, a literature review allows to present the state of the art regarding different technologies used to create a representation of an object surface. After analyzing and discussing them, a selection of solutions is established by identifying the right technologies meeting the specifications. Based on these technologies, products available on the market are selected. The final section summarizes the solutions that will be implemented and tested in the next chapters.
2. The second part describes the implementation of the selected solutions. An industrial robot belonging to the UCL is first detailed. It has already served for other master theses [4][5]. The sensing devices are embedded in it to hold and position them precisely. Afterwards, the procedure in order to implement the solutions is presented. Mechanical interfaces between the robot and the devices are designed taking into account several constraints. The data processing, the software used and the computations needed to place the laser head correctly compared to the skin are also presented.
3. The third part of this report is devoted to the comparison of the implemented solutions according to a defined experimental protocol. This experimental comparison contains the tests performed, the material used, the results obtained and finally the discussions leading to the choice of the final candidate.

Last but not least, several ways of improvements are proposed in order to have a critical look at the work done during this year and for a potential subsequent work.

This chapter starts by establishing the list of specifications of the complete system that will position the laser head with respect to the patient's skin. This complete system is composed of a sensing device and something to carry the laser head. To do so, it is important to clearly identify the client's needs. Indeed, it is often said that a good understanding of a problem provides half the solution.

Once all requirements of the system are listed, it is possible to identify the ones influencing the choice of the sensing device technology. From a state of the art gathering existing technologies linked to our need, a selection of feasible solutions is presented. Different possibilities are compared leading to a selection of devices available on the market based on predefined criteria.

1.1 Specifications

The first objective of this work is to clarify the client's needs by establishing a list of specifications (refer to Appendix A for the complete list).

The key elements that will limit the possibilities in the future discussion are the following :

1. FR 2.1: Adjust the laser head autonomously normal to the surface of the skin with a maximal error of 15° (two degrees of freedom).

As explained before, this is due to the temperature controller in the laser head which is not able to adjust the temperature correctly if the angle is more than 15° compared to the perfect vertical. The sensing device must therefore ensure that the laser head is positioned below this error limit in orientation.

2. FR 2.2: Position the laser head autonomously at a distance from the skin which is between 85 mm and 115 mm (one DOF).

As already discussed in the introduction, it is not possible to use the laser outside this distance range. Thus, the device must be able to measure the distance to the targeted skin surface to ensure that the laser head is positioned in this range before and during the stimulation process.

3. FR 2.4: The stimulated parts are the hand dorsum and foot dorsum. Both hands or both feet may be stimulated during the same experiment.

The sensing device must be able to work with skin properties and to see an area of minimum 30 cm x 31 cm. This area is enough to contain two feet with a shoe size of 48 (European size).

4. FR 2.5: Time between two stimuli : less than 10 seconds. One of the neurologist requests is to maintain or reduce the experiment duration. For now, it approximately takes 5 to 10 seconds to manually place the laser head for the next stimulus. As a consequence, the time to perform the measurement and the positioning of the laser head must be below 10 seconds.
5. C1: No contact with the patient. This is one of the most important criteria to take into account. The device is not allowed to be in contact with the patient skin. Otherwise, it would activate some mechano-receptors and would disturb the experiment whose purpose is to activate nociceptors only.
6. C3: Not disturbing the laser device. The sensing device must be completely transparent to the laser system to avoid disturbing the experiments.

Firstly, those requirements express the need of a robot to automatically position the laser head in the correct position. This robot is based on a device capable of determining the distance between the laser head and the stimulated area as well as its relative orientation. Both values allow to compute the correct position of the laser head. Therefore, the key function of the sensing device is to calculate the coordinates of points on the skin surface located in the laser direction. To retrieve these coordinates, depth sensing technologies need to be used. The following state of the art will focus on such technologies.

1.2 State of the art

The objective of this section is to review existing depth sensing technologies that the sensing device could use. To obtain 3D coordinates of multiple points on a surface, two techniques are identified :

1. The first technology is the *3D scanner*. A 3D scanner is a device that analyses an object or environment to create a 3D representation of it thanks to specialized software. The principle of such technology is illustrated in Figure 1.1. The 3D model consists of a collection of points belonging to the object surface in 3D space commonly called a *point cloud*. These points are then used to build the shape of the subject using various geometrical algorithms. This process is called *reconstruction*. 3D scanners are also able to collect data about the shape and appearance (e.g. colour or texture) of the scanned subject. Once the latter is reconstructed digitally, it can be exported to different file formats such as STL, OBJ, PLY and so on. STL files describe a raw, unstructured triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system. This file is printable using a 3D printer or can be used for other purposes.

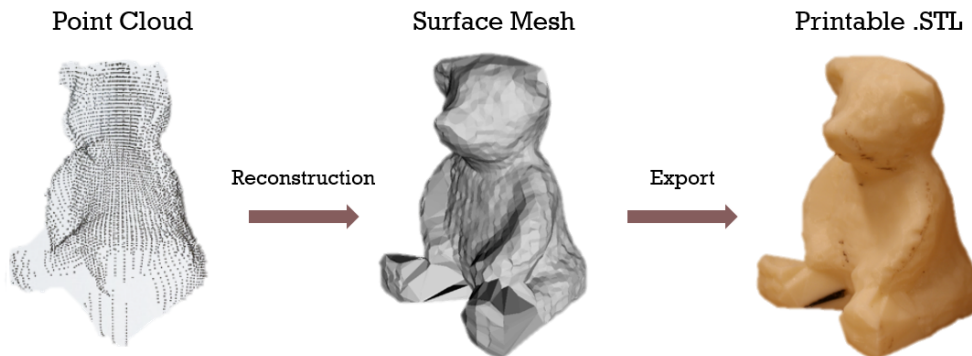


Figure 1.1: A 3D scanner digitizing a small bear (image inspired of [6])

Obtaining a 3D model of a subject is useful for a wide variety of applications. These devices are used extensively by the entertainment industry in the production of movies and video games, including virtual reality. Other common applications of this technology include industrial design, orthotics and prosthetics, reverse engineering, prototyping and quality control/inspection. This can also be used in our application because it is possible to extract and manipulate the 3D coordinates of all points composing the point cloud.

Several technologies are existing to build a 3D model of an object. Each technology comes with its own limitations, advantages and costs. They are presented in Section 1.2.1.

2. The second technology is the *distance sensor*. According to its name, this device measures the distance between an object and itself. Based on the known position and orientation of the distance sensor, the latter is able to provide the 3D coordinates of one point belonging to an object surface. If multiple sensors are used or if one sensor is moved and records measurements several times, it is possible to obtain the coordinates of multiple points. Unlike 3D scanners giving a *global* representation of a subject, multiple distance sensors are giving a *local* representation of it.

There are different types of distance sensors technology, each one dedicated to specific applications. More information is given in Section 1.2.2.

1.2.1 3D scanner

The 3D scan of objects is being developed since the 1960s. Today, several technologies can be used to 3D scan objects, environments, and people. Each one comes with its own limitations, advantages, and costs. This paragraph lists the main technologies, explains how each one works, mentions their pros and cons and highlights the ones that might be used for our application.

After research, five different technologies were found : laser triangulation, structured light, photogrammetry, contact based and time of flight.

Laser triangulation

Laser triangulation based 3D scanners use a laser line to scan across an object as depicted in Figure 1.2. To obtain the 3D scan, the deformation of the laser line projected on the object is observed by a camera offset from a certain angle (triangulation principle). The differences in height along the laser line are visible by the sensor in the camera and converted in a surface profile as seen on the computer of Figure 1.2. While the object is moving under the laser-line generator (or the opposite), new surface profiles are generated. Gathering profiles and using appropriate algorithms, it creates the object 3D model.

This technology is used for low range scanning (less than a meter). It is mostly used in the industry for surface quality because of its high resolution. The objects to scan are generally placed on a conveyor belt and flow under the scanner. Sometimes, the scanner is fixed on a robot end-effector like in Figure 1.3. In this case, the robot moves above the object to create a 3D representation of it.

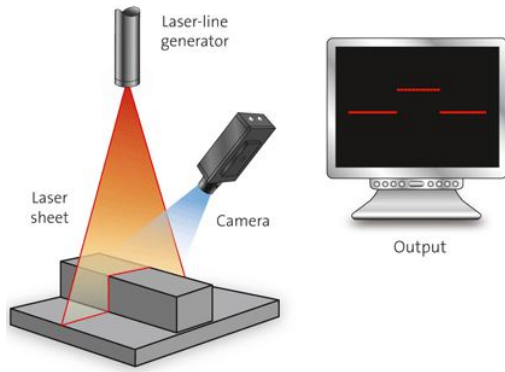


Figure 1.2: Illustration of the laser line triangulation principle [7]

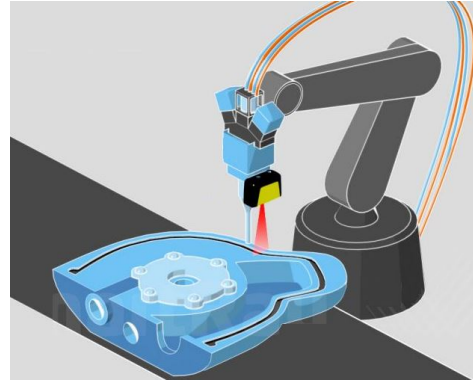


Figure 1.3: Laser triangulation embedded on an industrial robot [8]

One downside of this technology is its sensibility to the properties of the surface to be 3D scanned. Very shiny or transparent surfaces are particularly problematic. Another disadvantage is that a movement between the scanner and the object is mandatory to create the 3D model. This movement needs to be precisely known to reconstruct the object based on the different profiles generated. Therefore, the scanner needs a machine like a conveyor or a robot to perform its scan.

Concerning the cost, it depends on the product. On the one hand, industrial scanners using laser triangulation are very precise but need a robot or a conveyor and a very powerful computer to run the algorithms. An example is the 3D scanner of MICRO-EPSILON[®] presented in Figure 1.4. On the other hand, cheap scanners for individuals (around 400\$) are composed of a laser, a camera and a rotating plate. The CICLOP[®] 3D scanner in Figure 1.5 is one example. These scanners are dedicated to small objects. The resolution is 0.5 mm which is quite impressive. However, it takes up to height minutes to perform a scan of a complete object.



Figure 1.4: Laser triangulation scanner of MICRO-EPSILON[®] fixed on a robot scanning a welding [8]



Figure 1.5: The CICLOP[®] 3D scanner is composed of two lasers, one camera and one rotating plate [9]

Structured Light

The structured light technology is very similar to the laser triangulation. The system is also composed of a projector and an offset camera that observes the deformed pattern. However, this time, it is not a single laser line that is projected on the object. Instead, the projector emits a *structured light* onto an object like in Figure 1.6. This light pattern is known and is composed of horizontal bars, grids or a randomized dot matrix as depicted in Figure 1.7. By examining the edges of each line in the pattern, it is able to calculate the distance from the scanner to the object's surface [10].

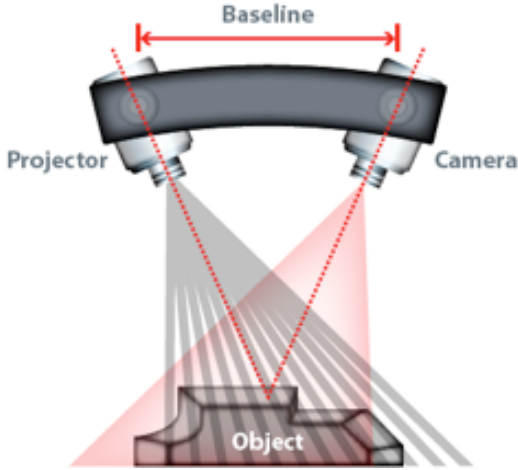


Figure 1.6: Structured light principle [10]

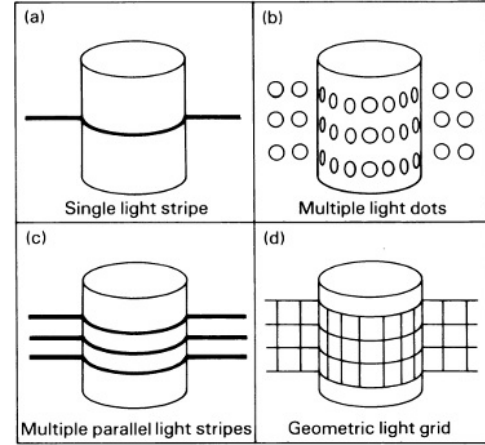


Figure 1.7: Kind of structured light patterns [11]

This technology is able to scan objects of different sizes. From small objects of a few centimeters to bigger ones measuring a few meters. To scan big surfaces, the user has to move over the object to scan the entire surface. The algorithm progressively reconstructs the complete object. In our case, the targets of Figure 4 in the introduction are small and relatively smooth so it might be possible to see the whole surface without having to move the scanner.

The main advantages of the structured light technology are its speed, resolution and ability to 3D scan people. One downside is its sensitivity to external light sources [12]. If the 3D scanner is in complete darkness, it is able to recognize the shape of the object but not its colors.

Concerning the cost, it depends on the scan quality. 3D scanners using structured light technology begins at one hundred dollars, like the Microsoft KINECTTM in Figure 1.8, to tens thousands of dollars like the scanners proposed by ARTEC[®] 3D in Figure 1.9. Their systems are dedicated to professionals and provide a high accuracy (up to 0.1 mm [13]).

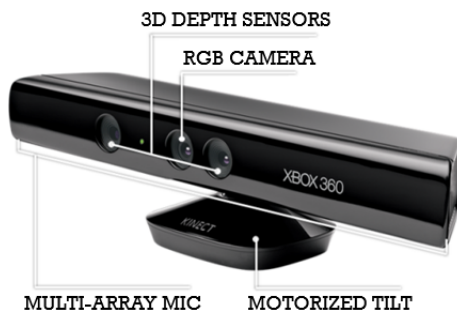


Figure 1.8: The Microsoft KINECTTM and a description of its components [14]

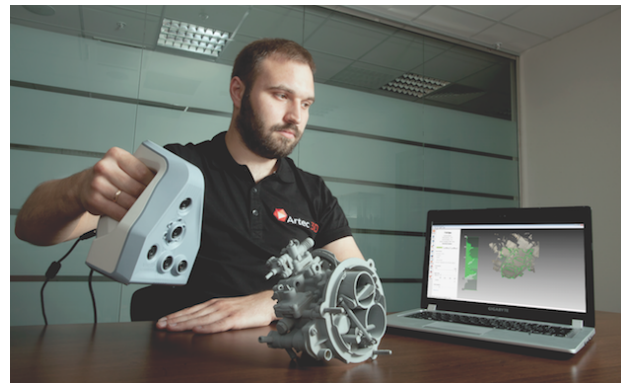


Figure 1.9: The ARTEC[®] spider 3D scanner in use [15]

The KINECTTM is also used to capture the movement of video game players in real time. However, the accuracy needed to capture such movement does not have to be very high. Indeed, a few centimeters is enough. But this is not the case for our application. Real time 3D scanners using structured light technology that are more performing begin to make their apparition, but are still at the research level [16].

Photogrammetry

Photogrammetry is based on a mix of computer vision and powerful computational geometry algorithms. It consists of making measurements from several photographs, especially for recovering the exact positions of surface points. If only two photographs are taken, the word *stereoscopy* is used instead. People are using this technique every day without knowing it using their eyes to see in three dimensions.

The photogrammetry principle is represented in Figure 1.10. The goal is to analyze different photographs of a static subject taken from different viewpoints. An algorithm will then detect pixels corresponding to a same physical point [17].

The main challenge for this 3D scanning technology is to analyze many photos and identify thousands of points with high accuracy. A very powerful computer is therefore required to limit the computational time.

There are different ways to use this technology. First, a classical camera could be used to take multiple pictures of an object from different angles. The 3D representation of the object is then built thanks to an algorithm. However, the time to take all these pictures and for the software to run the algorithm is very long. Moreover, it is not very accurate for surfaces relatively uniform like unicolor objects. Indeed, it is difficult to differentiate points on a uniform picture since the algorithm is looking for differences between images. Secondly, stereoscopic devices exist like the ZED[®] presented in Figure 1.11 embedded on a mobile robot. The device costs 450\$ [18]. It is composed of two cameras next to each other. The cameras are recording continuously such that the scanner is able to obtain a 3D representation of the environment in real time. This is very useful for example in robot navigation. The robot is able to navigate into its environment while avoiding obstacles.

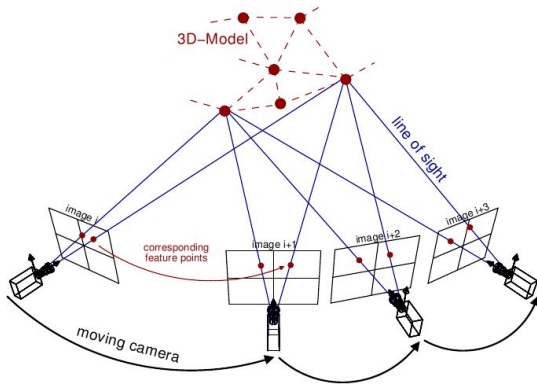


Figure 1.10: Photogrammetry principle: two dots of an object are detected by the camera in four successive positions [17]

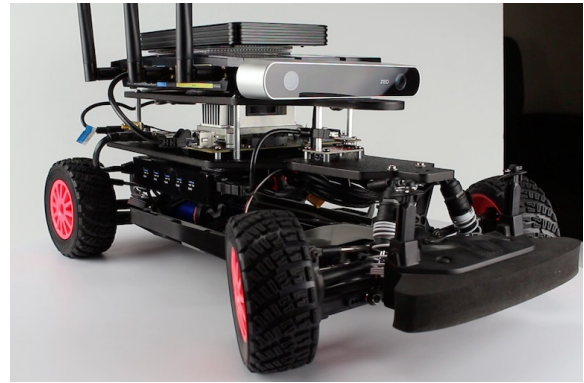


Figure 1.11: ZED[®] 3D scanner embedded on a mobile robot to help navigate in its unknown environment [19]

However, stereoscopy is used by middle or wide-range scanner. It means that the distance between the object to scan and the device has to be at least one meter. In addition, the associated resolution is too low for our application since it is in the range of the centimeter. This type of scanner is more likely to scan an entire room or furniture.

Contact based 3D scanner

According to their name, contact based 3D scanners imply a contact with the object to scan while the object is firmly held in place.

A touching probe is moved on the object surface from point to point in order to collect the 3D information. The probe is often attached to an articulated arm like in Figure 1.12. By knowing the angle of each arm's articulation, it is able to know the configuration of the end-effector (like direct dynamics in robotics) for each scanning point.



Figure 1.12: Example of contact based 3D scanner [20]

Contact 3D scanning is widely used in quality control of parts after being manufactured or during maintenance operations [12].

The main advantages are its precision and ability to scan transparent or reflective solid surfaces. However, its speed is limited, it is not convenient to work with deformable surfaces like the human skin.

This technique needs also a contact with the human body, which is not allowed.

Time of Flight

Time of Flight or ToF scanners evaluate the distance from the object by emitting a signal and looking at the reflected signal. The signal commonly used is infrared light.

There are two possible ways to determine the distance. Both are illustrated in Figure 1.13:

1. The first method is to emit a pulse and measure the time that the signal takes to come back. Then, by knowing very accurately the propagating speed of the signal, it is possible to compute the distance by multiplying both quantities.
2. The second method is to emit a sinusoidal signal and measure the phase shifting between the emitted and received signal. By knowing the signal frequency, it is possible to determine the time that takes the signal to make the round trip. Finally, the distance is computed as described before.

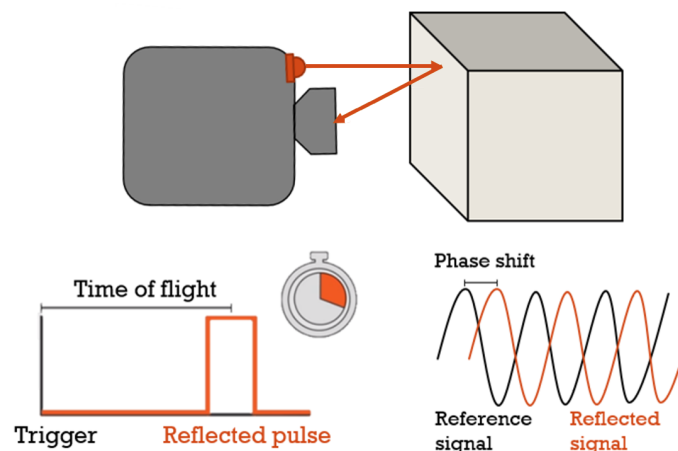


Figure 1.13: Illustration of two techniques using ToF principle (inspired from [21])

The 3D scanner measures the distance between the camera and the subject for each pixel of the image. It is thus possible to capture the entire scene in one shot. It computes the distance

point-by-point with a laser beam such as in scanning LIDAR systems.

A ToF camera makes fast computations. It is therefore possible to obtain a 3D map of the environment in real time. However, since the speed of light is very high, it is difficult to precisely measure the ToF for short distances. According to this, the LIDAR system is really dedicated to long-range scanning like the modeling of an entire building or a car as depicted in Figure 1.14.



Figure 1.14: Example of a LIDAR system used to scan a building [22]

ToF camera are sometimes used for lower range scanning but the depth accuracy is still about a centimeter. This is why this kind of system is mostly used for gesture recognition. Figure 1.15 represents a test of a ToF camera developed by TEXAS INSTRUMENTS™. The gesture recognition can be used in different applications like the interaction with objects in virtual reality. Another example is the control of interfaces. BMW® and VISTEON® propose a system of gesture control as an option for high standing vehicles [23, 24]. The device, presented in Figure 1.16, allows the driver to adjust the center console, windows, lights and more without having to touch anything.



Figure 1.15: Test of the TEXAS INSTRUMENTS™ ToF camera [25]



Figure 1.16: System of gesture control of BMW® using ToF [23]

Finally, some 3D scanners use the principle of echolocation as the bat. The principle is the same but using sound as a signal. This type of technology is made for obstacle detection and not for precise measurements of distances. The accuracy can reach 2 cm below 1 m of distance [26].

This closes our searches in the literature concerning the 3D scanning technologies. Before identifying which technology could be used for the final system, the same kind of research regarding distance sensor technologies is needed.

1.2.2 Distance sensors

Distance sensors are using various techniques to retrieve the distance separating them from an object. Each type of sensor has its own characteristics, measurement range, compatibility with materials and so on.

In our application, the distance is measured from human skin, no contact is allowed, and the measurable distance range must be wider than 70 mm which corresponds to the height of a foot. Knowing that, some technologies are already eliminated. For example, inductive sensors work with ferrous materials, confocal sensors have a maximum range of 30 mm [27] and the interferometry-based method has an even closer range [28, 29].

This section describes the distance sensor technologies that can potentially be used for a future solution. The pros and cons of three technologies are described.

Time of Flight

The ToF technology has already been presented in the previous section for 3D scanners. The difference here is that a distance sensor captures the distance to only one point of a surface instead of having a depth map of the whole scene.

As mentioned above, the ToF technology is based on the emission of a well-known signal that hits an object and reflects back to the sensor receiver. Again, there are two main types of signals that may be used : sound and light.

As illustrated in Figure 1.17, an ultrasonic distance sensor emits short bursts of sound and listens to its reflection [30]. Knowing the speed of sound (about 340 m/s) and the time of flight, the distance is calculated with the following formula :

$$\text{Distance} = \frac{v_{\text{sound}} \cdot ToF}{2} \quad (1.1)$$

where the factor 2 is used to consider only one way of the sound.

This technology has some downsides. First, since the sound is emitted in multiple directions, it is difficult to know which part of the object is detected by the sensor. Then, the speed of sound depends on environmental parameters such as air temperature, ambient humidity and so on. This technology is therefore not convenient for the sensing device since the objective is to obtain the accurate coordinates of a single point on the skin.

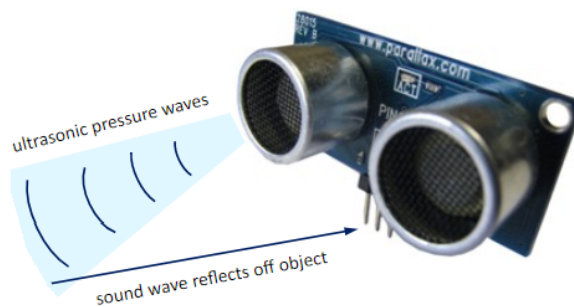


Figure 1.17: Example of ultrasonic sensor [31]

Infrared sensors are based on the same principle but using infrared light. An infrared sensor measures the distance with the phase shift methods described earlier. Since the speed of light

is a constant, the computation of the distance does not depend on environmental parameters. However, the speed of light is very high. It is therefore difficult to measure precisely the ToF of the signal. In particular, this type of sensor is less accurate for small distances. However, there exists sensors using ToF that work in low range distance.

Laser triangulation

The principle of the laser triangulation sensors technique is illustrated in Figure 1.18. It looks like the laser triangulation principle of the 3D scanner but instead of using a camera and a laser-line generator, the sensor sends a narrow laser beam onto the object. The laser then reflects off the object and is concentrated by a lens so that it hits a detecting element sensitive to light. When the distance between the sensor and the object changes, the laser beam reflects at a different angle. Therefore, the position where the reflected beam hits the detecting element changes accordingly. Using trigonometric triangulation, the system is able to compute the deviation angle. According to this angle, the distance from the object to the scanner is found.

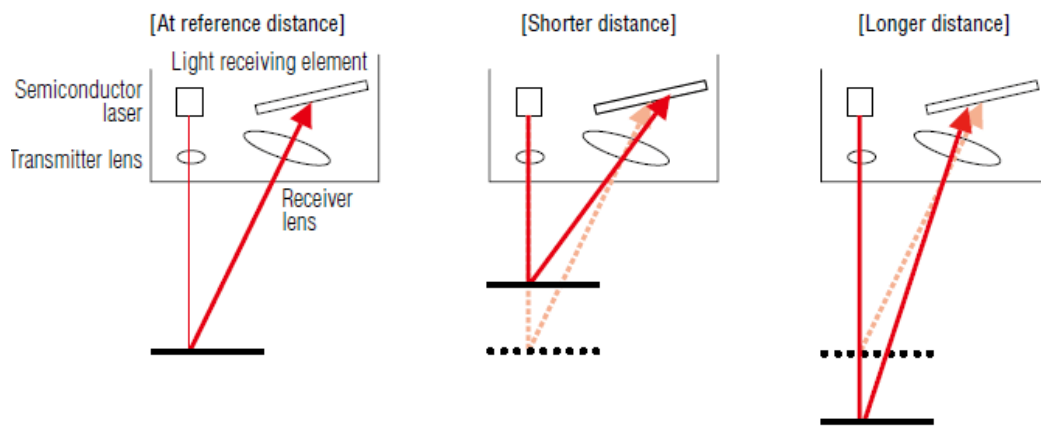


Figure 1.18: Laser triangulation working principle [32]

Conoscopic holography

Figure 1.19 illustrates the working principle of the conoscopic holography. Basically, the sensor sends a narrow laser beam focused with an objective lens and hits the object being scanned. A part of the reflected light travels back from the object into the sensor and enters the conoscopic unit. The latter contains an optically anisotropic crystal. The resulting interference pattern is detected, and complex signal processing algorithms are then used to retrieve the distance information from the measured data [33].

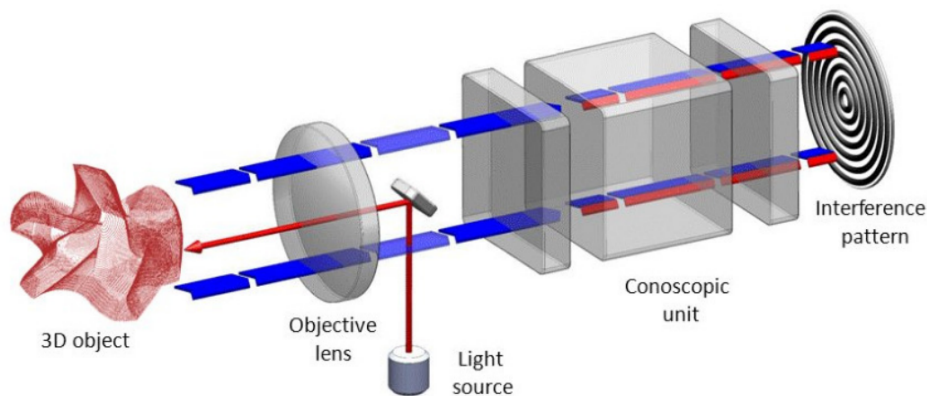


Figure 1.19: Conoscopic holography working principle [33]

This technology has multiple advantages. First, it is possible to choose the operating range by simply changing a lens. The device can reach the precision of a micron. The emitted and reflected signals are on the same line so that it can reach difficult locations as deep holes unlike the triangulation technique. Furthermore, the device stays accurate even for surfaces tilted of 85° .

The downsides of this technology are that only one company producing this type of sensor, named OPTIMET[®]. The price of these sensors is not communicated but these are dedicated to industrial quality analysis. However, those kind of sensors are generally imposing. The smallest sensor has a length of 10 cm and weights 0.4 kg.

This ends our research on existing technologies capable of measuring a distance without contact.

1.3 Selection of solutions

Based on our findings from the previous section, a selection of feasible solutions is presented.

1.3.1 3D scanner

The state of the art highlighted that some parameters change significantly when comparing different technologies. The distance range, the resolution or the ability to obtain a real time 3D representation of a scene are some of them. This influences the way the scanner will be used. For example, if the scanner is not able to record continuously, the neurologist will have to make a 3D scan before the experiment. In this situation, the patient must not move afterwards. Another possibility is that the scanner and the laser head could be fixed together, or the scanner could be placed externally. All these elements demonstrate that the choice of the scanning technology will influence the global system. Indeed, if the scanner is separated from the laser head, we will have to find a way to make the link between the scanner frame and the laser head frame. Possible solutions can be to fix the laser head on a robot, or on a multibody system equipped with encoders.

Technology choice

First, let us find the most suitable 3D scanner technology for our application before thinking about the global system. Indeed, these two elements depend on each other.

Based on the list of specifications developed in Section 1.1, it is possible to identify criteria that the 3D scanner has to respect. The technology used must :

- **not be in contact with the skin** : the contact with the skin would activate mechanoreceptors leading to an alteration of the experiments results.
- **provide a sufficient XY and depth resolution** : the resolution influences the quality of the target. The better the resolution, the better the skin details. Moreover, resolution has an impact on the computation of the correct laser head position.
- **have a short scanning and processing time** : another important criterion is not to increase the experiment duration since the latter is already tedious. If the scanner is able to scan in real time, there is no problem. If it is not the case, as mentioned before, the user would have to make one scan before the experiment and then the patient must stop moving. However, if the patient moves, the scan needs to be performed again. After discussing

with André Mouraux, a scanning and processing time of maximum three minutes could be tolerated.

- **not be too expensive** : even if this criterion is not the most important, there are some devices costing tens of thousands US dollars, which is too expensive for a master thesis. Our goal is to try a solution and if it is successful, more investments could be made in order to improve it in a subsequent work. There exist 3D scanners for less than one thousand dollars that could meet all requirements.

In order to sum up the above information, Table 1.1 shows the criteria fulfilled by each technology. The comparison is made between products that can be found on the market. Therefore, technologies that are at the research level are not taken into account, since the objective here is not to build our own system from scratch.

Technology	No contact	Accuracy	Time	Price
Laser triangulation for individuals	✓	✓	×	✓
Laser triangulation for professionals	✓	✓	✓	×
Structured light	✓	✓	✓	✓
Photogrammetry	✓	×	×	✓
Stereoscopy	✓	×	✓	✓
Contact based	×	✓	✓	×
Time-of-Flight	✓	×	✓	✓

Table 1.1: Comparison between 3D scanner technologies

The technology fulfilling all criteria is structured light. Another possibility could be laser triangulation which is also intended to scan small objects. This technology is divided in 2 categories. The first one concerns the products for individuals that everyone can buy like the CICLOP[®] described in the state of the art. These products work only for objects that are placed on a rotating plate fixed compared to the scanner. Moreover, it takes more time than structured light method since the laser line has to progressively cover the whole object surface. The second category concerns the products dedicated to professionals. Different suppliers are providing this type of scanner such as MICRO-EPSILON[®], KEYENCE[®] or SICK[®]. However, no prices are indicated on their website. Moreover, the implementation of this technology is more complex than structured light. As explained in the state of the art, to perform a scan using laser triangulation, a movement between the object and the scanner is needed. This movement needs to be known accurately to reconstruct the 3D model using the different line profile.

With structured light, this is not mandatory. The technology captures a whole surface instead of a line. A single view could be enough to obtain all coordinates of the points composing hand or foot dorsum. If a movement is needed to cover the whole target, the scanner does not need the information regarding the movement. The scanner itself is capable of assembling the different views using the common parts between those thanks to geometrical algorithms.

Finally, the state of the art presented products able to perform scans in real time. This is something which is impossible when using the laser triangulation.

Product choice

The objective now is to find existing products using structured light technology and choose the most suitable for our application.

Several 3D scanners using structured light technology are available on the market, the best known

being probably the KINECT™ developed by Microsoft®. Figure 1.20 gathers some products and their price.



Figure 1.20: Products using structured light technology available on the market [34]

Since it is not possible to compare all products, an arbitrary choice needs to be done. The last product, the ARTEC® Eva Lite represents the entire professional range of scanners. The price is of several thousand euros. At first, the idea is to test the principle of a solution. If the principle seems to work, more investments can be made in the product used. The precision of these type of scanners is a tenth of a millimeter that would allow to see most irregularities on a hand or a foot skin.

The other products proposed are less expensive. The product on the left is the KINECT™. Initially, this product is used for gesture recognition in video games. However, several projects on the web are using it as a 3D scanner. The advantage of this product is its ability to obtain a 3D map of the environment in real time. Unfortunately, this product cannot be applied to our application for different reasons. Firstly, the minimum range of the KINECT™ is 0.5 m. Some sources even mention that it is advised to place the object at a distance of minimum 0.8 m for a good rendering. This seems logical since the product is initially made to recognize people gesture at 1.5 m. This product characteristic makes impossible to scan the skin in real time with the product embedded on a robot. Indeed, the laser head stimulates the skin only when it is at 10 cm of it. However, it might be possible to put the scanner externally. For instance, the scanner could be fixed on top of the scene and observe it. In this situation, the laser head would always be above the hand so that the scanner would never see it. Finally, even if we remove the laser head of the scene between two stimulations, the precision would probably not be sufficient using only one view of the scene.

For all these reasons, we choose to not use the KINECT™ and we did not find any other commercialized 3D scanner using structured light that is able to scan in real time. The idea would be therefore to perform one precise scan of the scene before the experiment and then tell the patient to stop moving.

Some programs exist on the web to use the KINECT™ to scan objects by assembling different view of the scene. But this product is not designed for this purpose, the scan is less accurate compared to other products such as the STRUCTURED SENSOR or the SENSE.

These two last products are used to make 3D models of small or big objects. They both have a XY and depth resolution of 1 mm and are able to scan human skin.

In the end, we select the SENSE because the STRUCTURED SENSOR needs an iPad™ to work, which increases the cost. Moreover, the precision is not better.

The SENSE has multiple advantages. It is light, easy to handle and it is possible to fix it using a camera thread. Its software provides multiple options and a visual aid to the user performing a scan. Finally, we were able to test the product at the MAKILAB. It is a FABLAB (contraction of the words "fabrication laboratory") located at the UCL. The result of a scan performed at the MAKILAB is shown in Figure 1.21. The shape of the hand is well captured, so we choose to buy the latest version of the SENSE 3D scanner (2nd generation).



Figure 1.21: Scan of a hand performed at the MAKILAB

SENSE presentation

The SENSE is designed to be hand-held vertically using the grip, but it is also possible to fix it thanks to a threaded mounting hole at the bottom. The scanner contains an emitter which projects an invisible infrared laser pattern onto the object. The pattern consists of a multitude of parallel lines as in Figure 1.22.

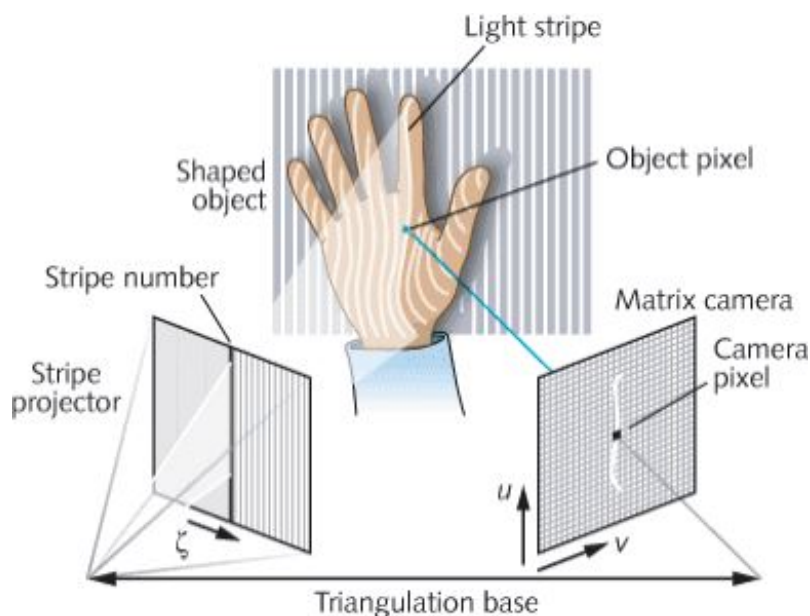


Figure 1.22: Infrared laser pattern of the SENSE [35]

It also has an infrared camera to capture the pattern deformation and a RGB camera to capture color information.

Table 1.2 gathers some of the SENSE features :

Features	Detail
Operating range	0.45 m to 1.6 m
Scan Volume	Min: 0.2 m $\times$ 0.2 m $\times$ 0.2 m Max: 2.0 m $\times$ 2.0 m $\times$ 2.0 m
Spatial x/y resolution @ 0.5 m	0.9 mm
Depth resolution @ 0.5 m	1.0 mm
Field of view	Horizontal : 45° Vertical : 57.5°
Size	17.8 cm x 12.9 cm x 3.3 cm
Operating temperature	10°C to 40°C

Table 1.2: SENSE features [36]

The scanner is easy to use and allows a data post-processing with several options thanks to its associated software. The latter can be installed on any computer supporting Windows 8/10 (64 bit) following this link¹. When the software is first opened, the SENSE must be plugged with the USB cable and the validation code must be entered. Once this is done, the scanner is ready to be used.

The procedure in order to obtain the 3D model of an object is the following. The numbers refer to Figure 1.23. Refer to the scanner datasheet [36] for more information.

- ① Select the kind of application : *Object* (any item other than a person), *Head* (a person's head and shoulders) and *Body* (a person's full body).
- ② Click on the *Options Menu* : it brings up a menu to adjust various parameters of the application.
Once all the parameters are set, the scanner is ready.
- ③ Once the scan is done, several options are available. The button *Export* is used to save the file in STL, OBJ or PLY format on your computer.

¹<https://www.3dsystems.com/shop/support/sense2/downloads>

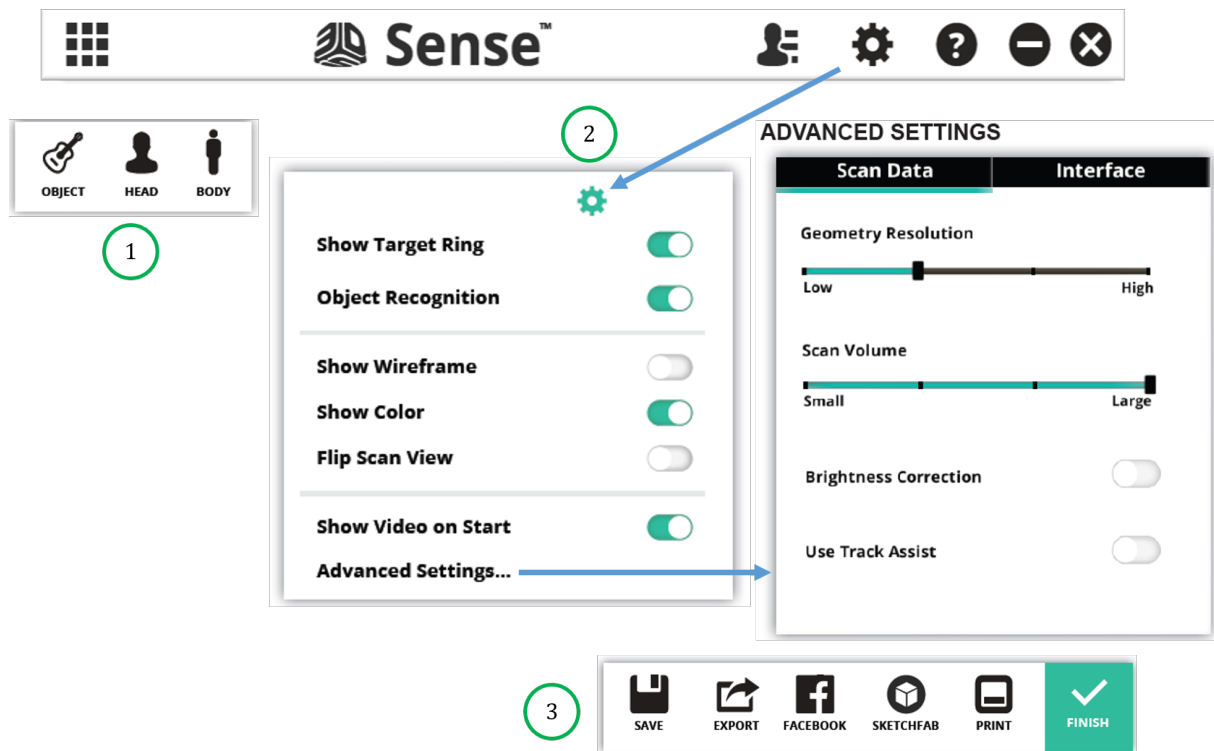


Figure 1.23: Software interface presentation [36]

Solution description

As a reminder, the complete system needs a robot to hold and move the laser head in space. Indeed, a robot possesses a very high accuracy and repeatability. Concerning the measuring system, we have to figure out how to use the SENSE to perform the measurements and translate them into movement instructions for the robot.

The first step is to find a way of extracting the coordinates of all points composing the 3D model and express them in the robot frame. Indeed, this is a mandatory step. If we want the robot to correctly position the laser head compared to the hand, we must first know where the hand is located compared to the robot.

To determine the frame in which the points of the 3D model are expressed, we extract the points of the 3D model and we plot them using the MATLAB[®] software. We choose to save the model in an OBJ format because it is easy to identify and manipulate the coordinates of all points composing the model. The structure of the .OBJ files generated by the SENSE[®] looks like in Figure 1.24. It contains several information such as the geometric vertices coordinates, the texture vertex coordinates and the triangles forming the 3D model. In our case, we only use the first quantity corresponding to the points belonging to the scanned surface. The coordinates are the three columns next to the letter 'v' inside the file.

Note that the texture could also be used to retrieve the color of the model. It could be useful for the implementation of a graphical interface.

```

# platform
#g Polygonal_Model_1 (null)
# Number of geometric vertices: 232501
v -10.91811 -23.15833 27.26705
v -10.07335 -23.15690 27.27640
v ...

# Number of texture vertex coordinates: 201388
vt 0.546460 0.024209
vt 0.546888 0.024841
vt ...

mtllib Objet_reference.mtl
#g Polygonal_Model_1 (null)
usemtl ml
#g Polygonal_Model_1_Triangles_Component1
# Number of triangles: 399781
f 1/1 4/2 3/3
f 1/1 3/3 2/4
f ...

```

Figure 1.24: Structure of an OBJ file generated by the SENSE[®]

Figure 1.25 shows the result obtained for a scan performed manually. We see in this point cloud that the model has a strange orientation. The logic behind is that the frame in which the coordinates are expressed corresponds to the frame of the first image taken by the scanner. For the point cloud in Figure 1.25, the scanner was initially tilted as illustrated in Figure 1.26. The scanner frame is also represented in this picture.

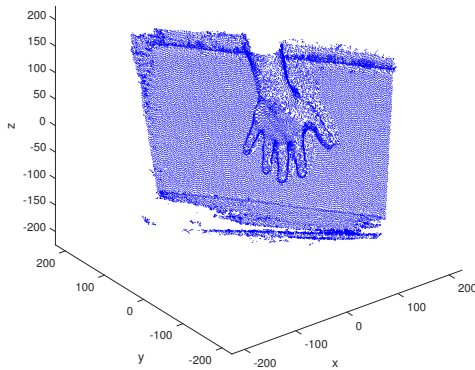


Figure 1.25: Point cloud of a hand on a table where the scan is performed manually

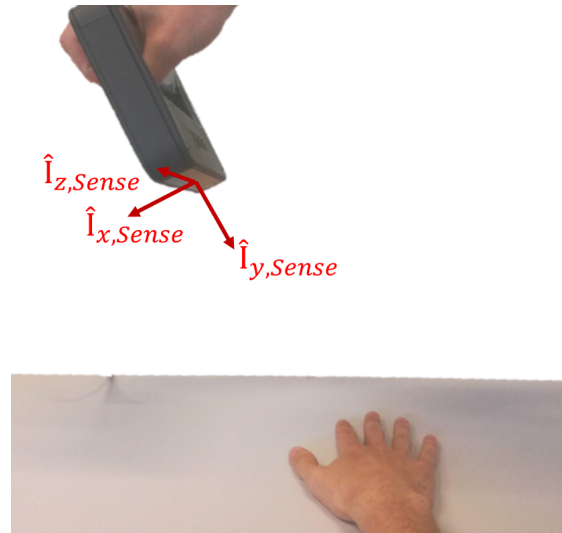


Figure 1.26: Situation where the scanner is tilted when starting the scan

Figure 1.25 shows a second important observation. The zero coordinate of each axis is right in the center of the 3D model. This is better illustrated in Figures 1.27 and 1.28. It means that the coordinates of the point could only depend on the size of the object itself. It does not have a relation with the environment around it.

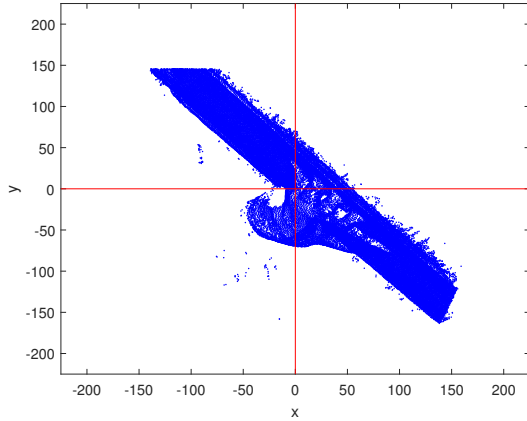


Figure 1.27: XY view of the point cloud

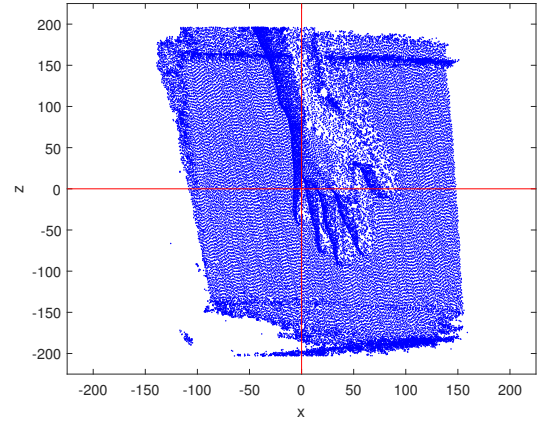


Figure 1.28: XZ view of the point cloud

Then, how is it possible to link the scan frame to the robot frame ? A solution is to identify some parts inside the scan corresponding to the real world. Then, knowing where these parts are compared to the robot, it is possible to compute the transformation between the scan frame and the robot frame.

For example, on the present point cloud, the table on which the hand is positioned can be clearly identified. The table could correspond to the plan $z = 0$ in the robot frame. However, this is not enough to make the link between both frames. One way to ensure this is to place an object like a cube inside the scan. This object must have known dimensions and be precisely positioned. The edges are then identified in the scan frame to make the link with the robot frame. However, identifying parts inside the scan is not so easy and if the scan is made by hand, the boundaries of the scan will always change as well as the transformation. Using a robot to perform the scan should always give the same boundaries to the scan and the transformation could be computed only once.

This leads us to the conclusion that the complete system would be composed of a robot equipped with both the laser head and the SENSE. The devices would be fixed on the robot end-effector because they need to be positioned with a high accuracy and precision. The robot would first perform the scan using the SENSE. Then, using the generated 3D model, it will be possible to compute the position where the robot would have to position the laser head. However, to translate it into a movement instruction for the robot, a link between the frame of the robot and the scan is needed. This link will be determined thanks to a reference object. The computation of this transformation will be done in Chapter 2.

1.3.2 Distance sensors

As for the 3D scanner, a solution using a distance sensor can be used for the sensing device.

Possible solutions

As explained before, a distance sensor allows to determine the coordinates of one point at the surface of an object. However, it is necessary to know the position and orientation of the sensor. To determine the position of the laser head, the same robot as for the 3D scanner is used.

To compute the normal of the surface targeted by the laser, the coordinates of at least 3 points must be known. There are different ways to obtain these coordinates :

1. Figure 1.29 : Use 3 or more distance sensors fixed together on the robot end-effector and obtain at least three measurements between each stimulation (planar approximation). Each sensor, emitting a beam parallel to the laser head beam provides the distance to one point of the skin surface.
2. Figure 1.30 : Use 1 distance sensor fixed to the robot end-effector. This time, the robot itself moves to obtain at least three measurements between each stimulation.
3. Figure 1.31 : Use 1 distance sensor fixed to an actuator itself fixed on the robot end-effector. In this case, instead of the robot, it is the actuator that controls the position and orientation of the sensor to obtain the measurements.
4. Figure 1.32 : Use 1 distance sensor fixed to the robot end-effector. Before the experiment, the robot goes all over the hand or foot dorsum following a grid to create a 3D representation of it.

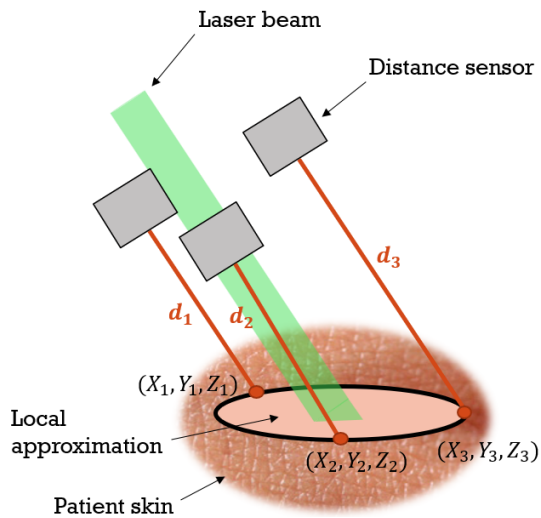


Figure 1.29: 3 or more distance sensors obtaining 3 measurements of points belonging to the skin surface

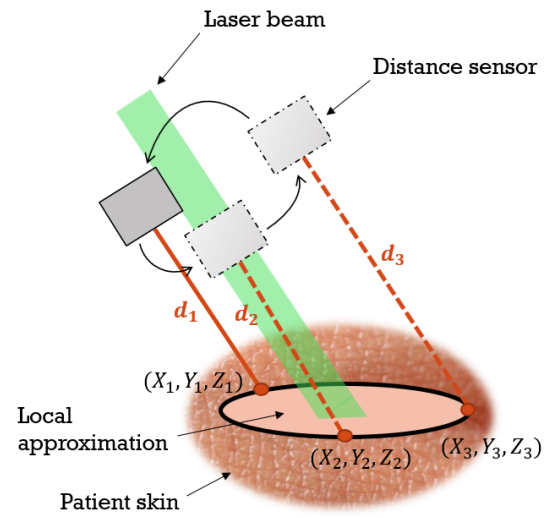


Figure 1.30: 1 distance sensor obtaining 3 measurements by moving the robot in 3 different positions

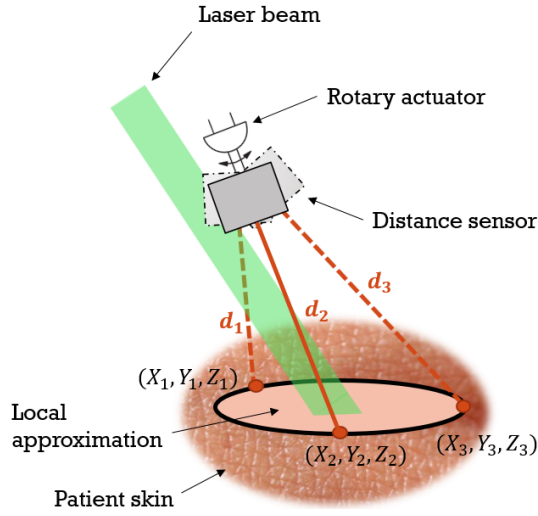


Figure 1.31: 1 distance sensor with an actuator moving the sensor in 3 different positions

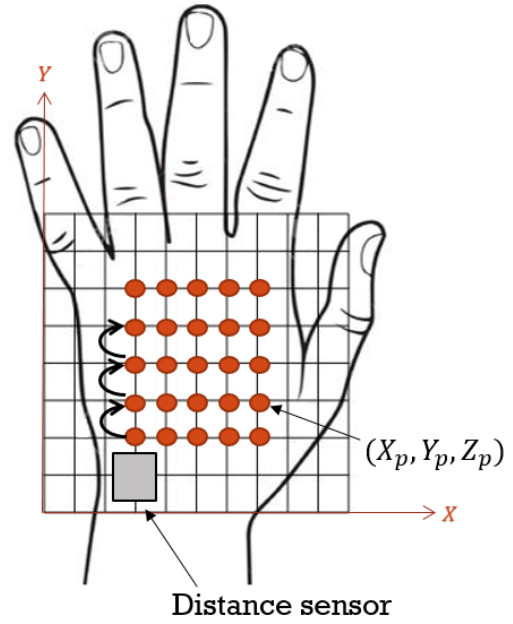


Figure 1.32: 1 distance sensor constructing a grid of points by moving the robot

Strategy selection

The first three solutions create a new local approximation of the skin surface between each stimulation. It means that even if the patient moves between two stimuli, the device is still able to make a correct approximation of the target. However, the last solution does not. It only makes one set of measurements before the experiment. In this case, it is similar compared to a 3D scanner but with a lower resolution and with a much longer time. This solution is therefore rejected.

Then, the third proposition is to add an actuator on the robot to move the sensor and get multiple measurements. However, the robot has enough degrees of freedom to place the sensor in any position and any orientation in its workspace. Thus, there is no need of an extra actuator since it adds cost and complexity to the system.

There are two remaining solutions. The first one uses three or more distance sensors fixed together on the robot end-effector. The second uses only one distance sensor. The robot moves around the targeted surface to obtain at least three measurements. However, it takes time for the robot to move and stop at three different locations above the skin. Indeed, the robot will move next to a human. Its speed needs to be limited for safety reasons. The list of specifications mentions that the system has ten seconds to perform the measurements, the computations and placing the laser head in the correct pose. Therefore, the second solution is too slow. Moreover, if the patient moves between two sensor measurements, the position of the laser head calculated will be completely false.

For all these reasons, the first solution is the most convenient for our application. Indeed, it takes only some milliseconds to obtain the coordinates of three points of the skin surface in the same time. This will provide a new local approximation of the targeted surface in less than a second. In this way, even if the patient moves between two stimulations, the sensing device will still send a good position instruction to the robot since it is continuously actualized.

Requirements

In this review, different technologies used to measure a distance from an object are presented. The technology has to meet some requirements to be selected for the final solution. Since the sensors are fixed on the robot with the laser head, the measured distances are only a few centimeters. This limits the workable sensors to the ones with small range detection.

Determining the precision and accuracy needed is not a piece of cake. The precision of a sensor refers to the fact that all measurements are close to each other. Measurements without noise correspond to a high precision. A high accuracy means that all the measurements are located around the real value measured.

To find the needed precision and accuracy, Figure 1.33 illustrates a representation of the system using three sensors. The small cubes represent the three sensors and the part in green represents the laser head beam (6 mm wide). The laser beam is the center of the circle formed by the three sensors as shown in Figure 1.34.

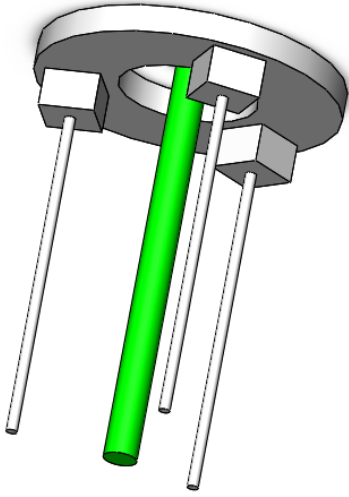


Figure 1.33: Illustration of the working principle of the system using 3 distance sensors

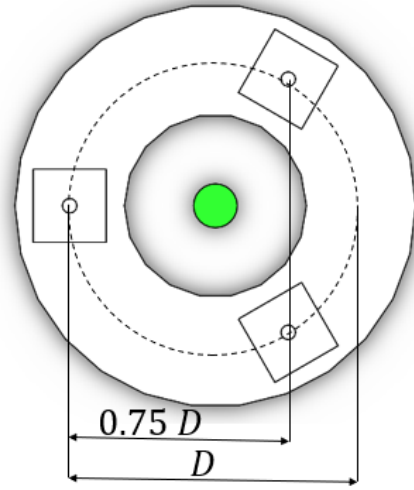


Figure 1.34: Bottom view of the system of 3 sensors

Figure 1.35 illustrates the situation where the laser beam is perpendicular to the surface. In this configuration, every sensor is measuring exactly the same distance. Nevertheless, every sensor has a limited accuracy. For example, imagine that the left sensor measurement has an error of $+\epsilon$ compared to the real distance and that the right sensors measurements have an error of $-\epsilon$. This case corresponds to the worst scenario. As a consequence, the system induces a tilting angle due to the relative difference in measurement equal to 2ϵ . This phenomenon is presented in Figure 1.36 where α corresponds to the angle induced by the error ϵ .

The induced angle α can be computed as following :

$$\alpha = \arctan \left(\frac{2\epsilon}{0.75D} \right) \quad (1.2)$$

This relation shows that the angle induced depends on the distance error ϵ and on the distance between the measured points D .

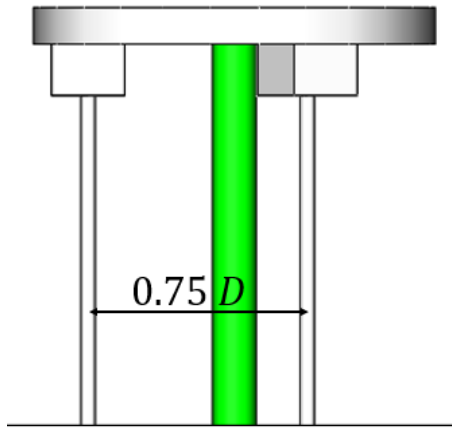


Figure 1.35: Lateral view of the system of 3 sensors when all sensors measure exactly the same distance

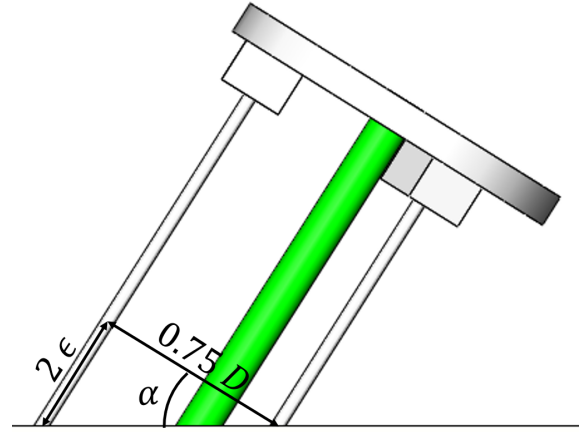


Figure 1.36: Lateral view of the system of 3 sensors when the sensors measure different distances

Figure 1.37 plots this relation for different values of D . As D increases, the error on the sensor measurement ϵ is less impacting the induced angle. Placing the sensors on a circle of 40 mm diameter allows an error of 4 mm on the sensor measurements. According to this result, the sensors should be spread as far as possible.

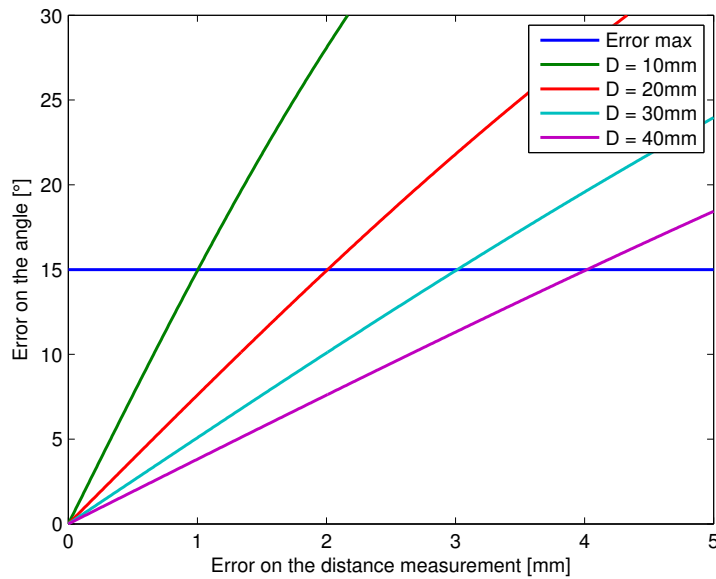


Figure 1.37: Evolution of the error in angle in function of the error in distance and the space between the measurements (D)

However, if D is increased, the approximated surface will not look like the one around the laser beam. Indeed, hands and feet are curved. Moreover, the three sensors must measure the coordinates of points belonging to the hand or the foot. If the measured points are too far from each other, there is a higher probability that one of them points towards an area outside the hand or foot as illustrated in Figure 1.38. In fact, there is an unreachable zone for the laser because of the system structure. The most critical case corresponds to $D/2$.

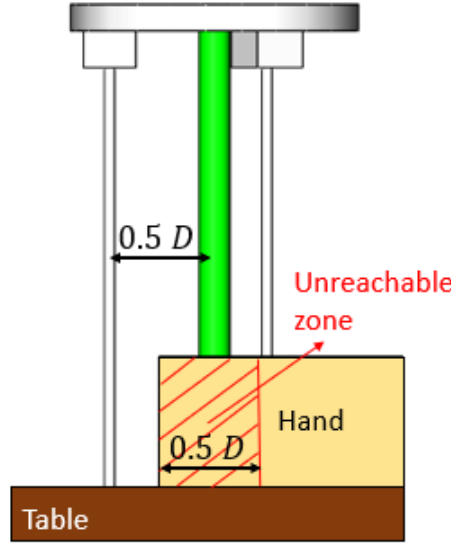


Figure 1.38: Situation where one of the sensors is pointing towards the table

Figure 1.39 reminds the zones that the neurologist is stimulating. The distance from the edge of the hand or the foot is about a centimeter. As a compromise, a distance D of 25 mm is chosen to be able to stimulate almost the whole desired area. At the same time, the diameter is wide enough to limit the induced angle caused by ϵ . The latter must be below 2.5 mm.



Figure 1.39: Stimulation areas for the experiments : hand and foot dorsum

Finally, measurement errors is not the only factor influencing the orientation of the laser. Another source of inaccuracy is the presence of irregularities. Indeed, one sensor could potentially points towards a vein as illustrated in Figure 1.40. The position of the laser will be affected because this sensor measures a smaller distance than the others.

It is possible to include this variable in the expression of equation (1.2) :

$$\alpha = \arctan \left(\frac{2\epsilon + h}{0.75D} \right) \quad (1.3)$$

where h is the height of the skin irregularity.

It is supposed that skin irregularities of a patient is less than 2 mm in height. According to this hypothesis, and by fixing D to 25 mm, the evolution of the angular error as a function of ϵ is presented in Figure 1.41. This final graph shows that the sensors must now have a maximal

measurement error of 1.5 mm to perform the task correctly. However, the fact that all these exceptional cases occur at the same time is unlikely to happen. Research can be extended to sensors having an accuracy of a millimeter and a precision of a few millimeters. The latter can be decreased using data processing afterwards.

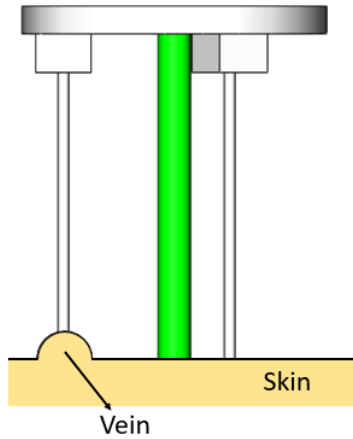


Figure 1.40: Situation where one of the sensors is pointing towards a vein

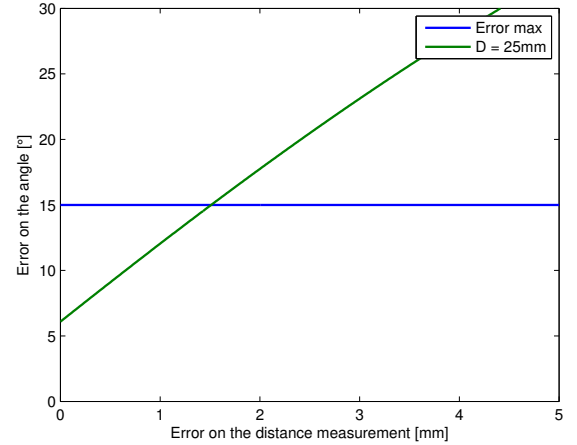


Figure 1.41: Evolution of the angular error in function of the error in distance for a fixed space between measurements (D)

Last but not least, the sensor technology must be able to operate with skin texture. As a consequence, it must not be too sensitive to the object reflectance since it could change significantly from one person to another.

Technology and product selection

Based on the list of criteria that the sensor must respect and based on the distance sensors overview, three technologies are identified for the final solution. These are the following : infrared sensors using ToF principle, laser triangulation and conoscopic holography.

However, the sensors of OPTIMET™ are too heavy and too big to embed three of them on the robot. Moreover, these are expensive. Note that if the solution using three distance sensors seems to work correctly at the end, more expensive sensors with better performances could be employed.

Concerning the two remaining technologies, the laser triangulation should be more accurate at lower distances because it is difficult to measure the ToF when the distance is short. However, for both technologies, it is possible to find products that are small, light, having all the needed characteristics and that cost only about ten euros. For this reason, two different sensors are bought : one using the ToF principle and another using the laser triangulation. The chosen sensors are presented in Figures 1.42 and 1.43. The first one is the SHARP GP2Y0A41SK0F using laser triangulation and the second one is the VL6180X which is an infrared sensor using the ToF technique.



Figure 1.42: SHARP GP2Y0A41SK0F sensor using laser triangulation [37]



Figure 1.43: VL6180X sensor using ToF [38]

The SHARP GP2Y0A41SK0F is a distance measuring sensor unit composed of an integrated combination of a position sensitive detector (PSD), an infrared emitting diode (IRED) and a signal processing circuit. Variation in reflectivity of the object, environmental temperature and operating duration are not influencing the distance detection [37].

This device outputs the voltage corresponding to the detection distance. An example of transfer function can be found in Appendix C.

Table 1.3 gathers the SHARP features.

Feature	Detail
Distance measuring range	4 to 30 cm
Output type	Analog output [mV]
Package size	29.5 mm (w) × 13.0 mm (h) × 13.5 mm (d)

Table 1.3: GP2Y0A41SK0F features [37]

The VL6180X allows absolute distance to be measured independently of the target reflectance (Appendix B). Instead of estimating the distance by measuring the amount of light reflected back from the object (influenced by color and surface), the VL6180X measures the time the light takes to travel to the object and reflects back to the sensor [39].

The sensor package of Figure 1.43 combines in a tiny space an IR emitter, a range sensor and an ambient light sensor (ALS). The module is designed for low power operations. Ranging and ALS measurements can be automatically performed at user defined intervals. Result reading is performed using an I2C interface. Optional additional functions, such as measurement ready and thresholds interrupt, are provided by two programmable GPIO pins.

Table 1.4 gathers the VL6180X features.

Feature	Detail
Distance measuring range	0 to 15 cm (refer to Appendix B)
Output type	Distance [mm]
Package size	4.8 mm (w) x 2.8 mm (h) x 1.0 mm (d)

Table 1.4: VL6180X features [39]

Comparison between SHARP and VL6180X

Figure 1.44 compares the raw data of both distance sensors for 10 seconds. The sensors are facing a flat surface. The distance separating the sensors from the surface is approximately 65 mm.

An ARDUINO board is used to read the output of the sensors. To retrieve the analog voltage sent by the SHARP sensor, a conversion is needed. Indeed, the sensor output is comprised between 0 and 5 volts but the ARDUINO board delivers a 10 bits binary because of the analog to digital converter (ADC). There are therefore 1024 values for the ARDUINO output where 0 corresponds to 0V and 1023 corresponds to 5V. To make the conversion between the ARDUINO output and the real analog output voltage of the sensor, the following transformation is applied :

$$\text{Output}_{\text{sensor}}[V] = \text{Output}_{\text{Arduino}} \cdot \frac{5[V]}{1023}$$

Since the VL6180X output is already digital, the conversion is not needed

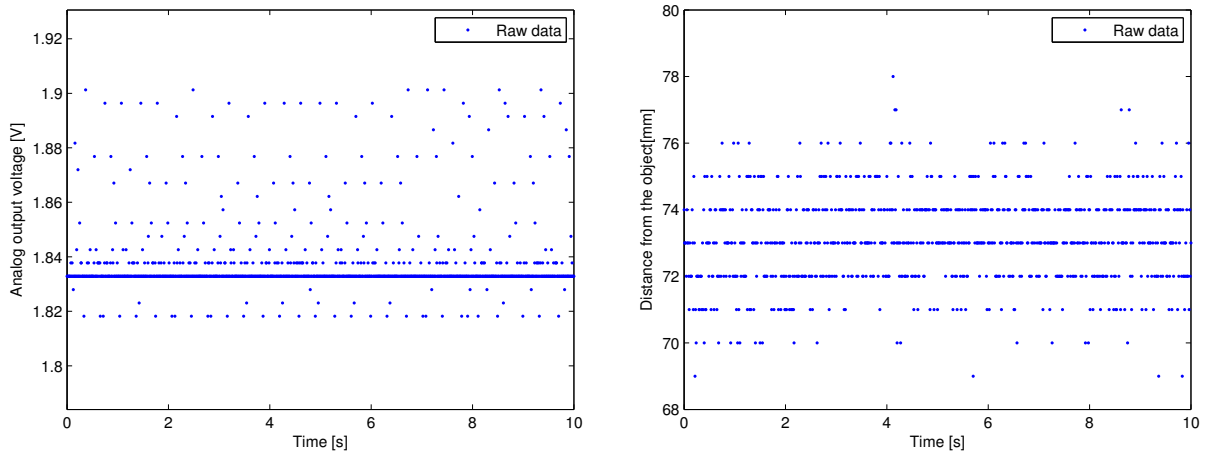


Figure 1.44: Comparison of the raw data of both sensors during 10 seconds

The SHARP output is varying from 1.8 to 1.9 V. By using the transfer function of the datasheet in Appendix C, it means that the measured distance varies approximately from 62 mm to 64 mm.

A 10 minutes recording is used to observe the evolution of the mean value of the output. The goal is to see if it remains stable during a long use. The mean value is computed every 100 measurements. The VL6180X mean output is not constant over time as depicted in red in Figure 1.45.

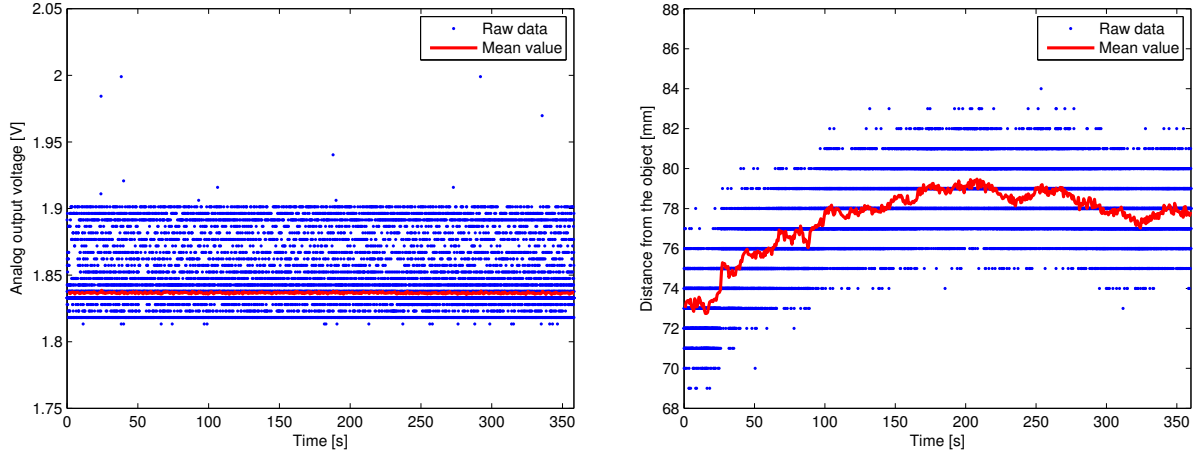


Figure 1.45: Comparison of the mean value of both sensors during 10 minutes

In conclusion, the SHARP seems better than the VL6180X. Indeed, the variation of the SHARP is 2 mm while it is almost 5 times greater for the VL6180X. Moreover, the SHARP mean output is almost constant over time whereas it is not the case for the VL6180X. This strange behavior is maybe due to the self-heating of the sensor inducing a temperature drift. In the end, for this particular application, the SHARP sensor is better in terms of performance and will be used for the final solution. As its output mean is almost constant, its ϵ is lower than 1.5 mm and therefore meets the constraint expressed earlier.

1.4 Summary

In the end, two feasible solutions are represented in Figure 1.46 :

1. A 3D scanner (SENSE 2nd generation) to scan the whole patient's hand or foot before the experiment and compute the correct position of the laser head based on the 3D model generated.
2. 3 SHARP distance sensors fixed together giving a local approximation of the patient's hand or foot. The correct position of the laser head is then computed based on the three sensor measurements.

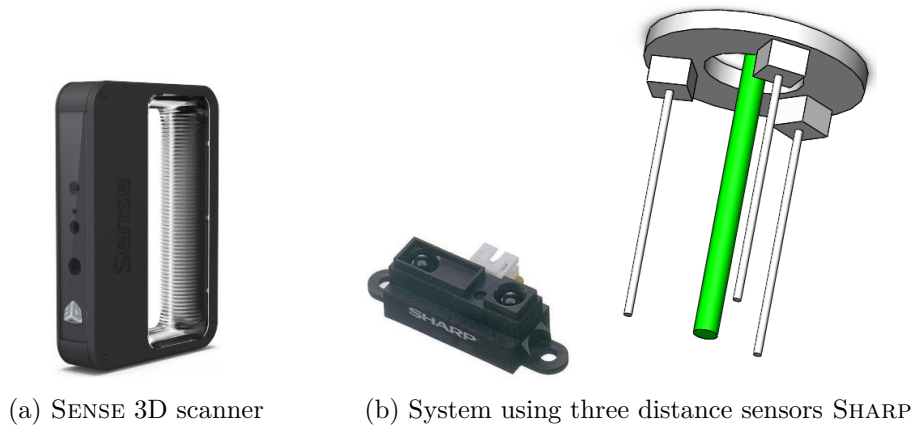


Figure 1.46: Summary of the chosen solutions

An interesting compromise appears. On the one hand, there is a solution using a commercialized product with a known resolution but having the disadvantage that the scan needs to be performed again if the patient moves. On the other hand, there is a solution using a homemade device. It has the advantage of being cheap and adapted to the application because, even if the patient moves, the experiment does not have to be paused.

Both solutions look promising. However, it is not possible to differentiate them on paper since they are fundamentally different. The next chapters of this report describe how both solutions are implemented and compared to choose the best candidate. If no solution wins, is it possible to combine them ? But then, are there interferences between both systems ?

In the previous chapter, two solutions for the positioning device were suggested. These solutions have to be implemented in order to compare them experimentally. This chapter presents the procedures followed to implement both solutions. Three sections are presented. The first section describes the industrial robot used to test both solutions. The second one explains the implementation of the solution using a 3D scanner. Finally, the third one describes the implementation of the device using three distance sensors.

2.1 The robot and its controller

An industrial robot is used because of the need of a high accuracy and repeatability to characterize both solutions. Note that this robot is only employed for this purpose and could not be part of a future complete solution. Indeed, the *Viper s650* robot was bought by Olivier Cartiaux 10 years ago and will be used for his researches at the end of this master thesis. However, integrate it to test our devices could motivate André Mouraux to buy his own robot.

2.1.1 Robot description

The *Viper s650* is manufactured by the firm *Adept-Cerebellum*®. It is an anthropomorphic industrial robot of 6 axes, having 6 degrees of freedom as depicted in Figure 2.1.

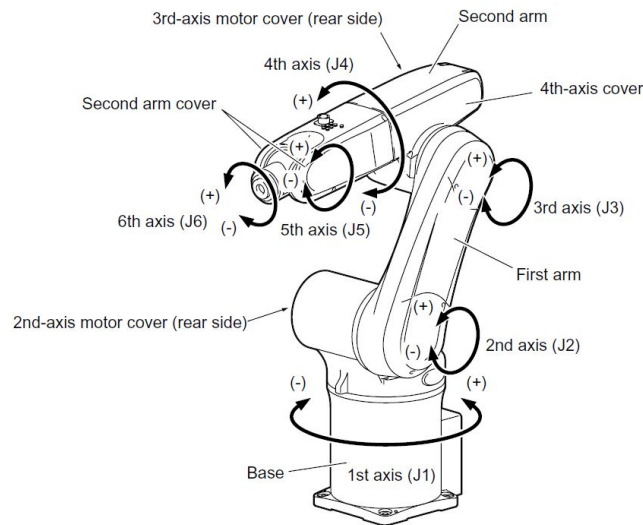


Figure 2.1: Robot Axis Identification [40]

Each joint is controlled thanks to its own motor. The end-effector is the part of the arm on which a tool can be fixed such as a milling machine, a saw, etc. The tool connected to this end-effector is free to move with 3 degrees of freedom in translation and 3 degrees of freedom in rotation. The end-effector is able to reach a radius of more than 650 mm, giving to the robot an important workspace (refer to Appendix D).

The robot characteristics are interesting since it has a positioning repeatability in (X, Y, Z) of ± 0.02 mm. Moreover, it has a high payload/total mass ratio of 2.5 kg / 28 kg. This robot is therefore the perfect tool to position our devices in space with high precision.

2.1.2 How to control the robot

The *Viper s650* was also used in previous UCL master theses. Those works [4][5] gave us a lot of information on how manipulating the robot. This section is therefore based on these reports.

The robot is piloted by a Cerebellum® controller. It contains all power electronics and a processor for executing code. It is therefore necessary to go through an intermediate computer in order to compile and send the code to the Cerebellum controller (by FireWire). The computer on which the user can write his program is provided with an appropriate license key and the CIDE software. In this C language environment, a series of high-level modules and functions are available. It is able to perform matrix operations and changes regarding reference frames.

The robot end-effector can be moved in two ways. It depends on the nature of the instructions sent to it. Figure 2.2 summarizes both methods.

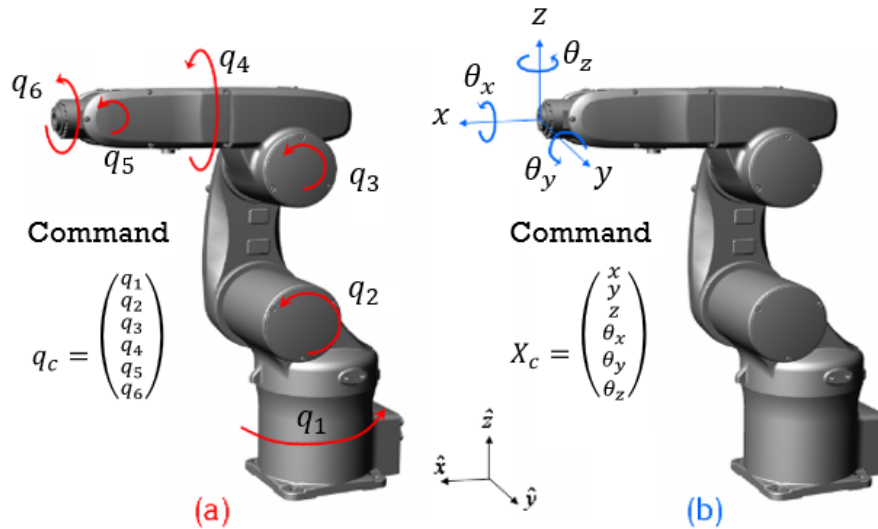


Figure 2.2: 2 types of robot commands : (a) Joints (b) Cartesian [4]

The first method is used to control the robot axes directly. The position controller ensures that each axis of the robot reaches the desired angular position. It is commonly called a ‘joint command’. The second method acts on the real degrees of freedom (DOF) of the effector. The end-effector has 3 DOF in translation and 3 DOF in rotation. This operational control is named ‘Cartesian command’.

The link between a joint configuration of a serial robot and the corresponding position and orientation of its end-effector is ensured by the direct geometric model of the robot.

Finally, for security reasons, a box allows a user action to start the program or to trigger an emergency stop button in case of problems.

2.1.3 Interface piece

To embed both devices on the robot end-effector, mechanical interfaces are designed. The first piece is shown in Figure 2.3.

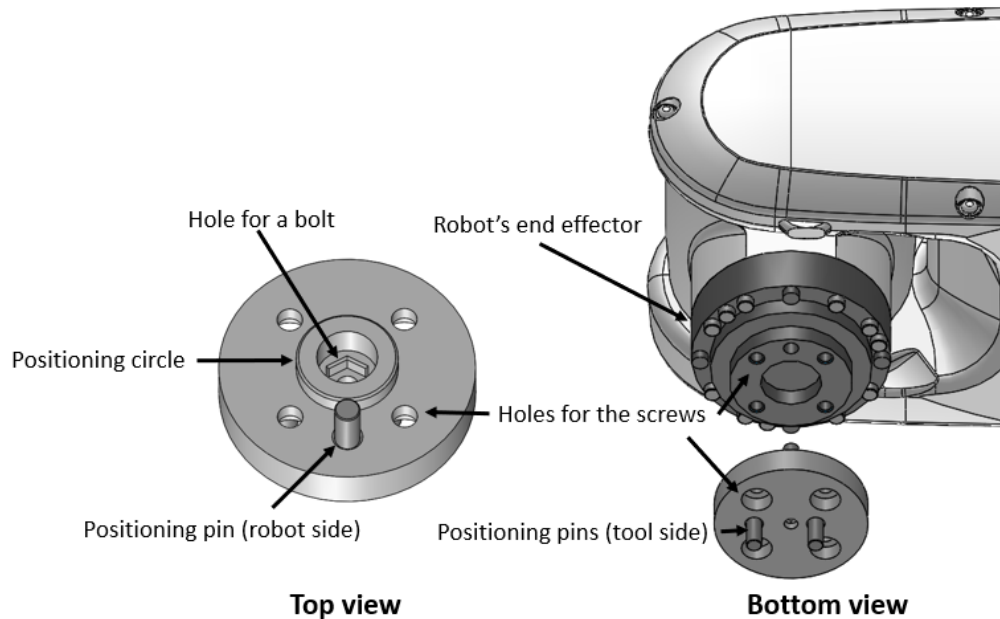


Figure 2.3: SOLIDWORKS® model of the mechanical interface between the tool and the robot end-effector

On robot side, the piece is placed thanks to the inner circle and one positioning pin. It is fixed on the end-effector with four screws.

On the other side, the tool orientation is forced by two positioning pins. It is fixed with a screw going through the central hole until a bolt is laid in the piece as depicted in Figure 2.3.

2.2 3D scanner implementation

The aim of this section divided in three parts is to describe the solution using the 3D scanner. The first part details how we designed and built the mechanical interface fixing both the SENSE and the laser head together on the robot end-effector. The second one reports the tests performed with the robot to determine the set of parameters giving the best scan for our application. Finally, the third part explains how computing the correct position of the laser head during the experiment. These calculations are only based on the scan performed at the beginning of the experiment.

2.2.1 Mechanical interface

The goal of the interface is primary to firmly fix the 3D scanner and the laser head on the robot end-effector. It is also used to precisely position them.

This has two objectives. The scanner frame is associated with the first image taken by the scanner. It is important to know the position of this first image in order to make the link between the frame of the object scanned and the robot frame. Furthermore, the position of the laser head to find the zone it is targeting must be known.

The design needs to take into account several constraints :

- The assembly must not restrict the robot workspace.
- Each element needs to be easily removed from the assembly. Indeed, the neurologist uses the laser for other purposes like for Magnetic Resonance Imaging (MRI).
- The assembly must withstand the stresses caused by the rigidity of the optical fiber jointed to the laser head. The optical fiber has a minimum curvature radius of 25 cm. Some problems in robot mobility could appear if the design does not take this parameter into account.
- USB cable of the 3D scanner.

The complete system is presented in Figure 2.4. It is composed of the laser head in green, the SENSE in red and three interface pieces.

The assembly illustrated in Figure 2.5 is positioned and connected to the piece illustrated in Figure 2.3 thanks to two pins and one screw. There are five holes on the top instead of three. The two additional holes allow to position the assembly in two different orientations on the robot end-effector.

The laser is assembled using the threading on the bottom to fix it to the rectangular piece illustrated in Figure 2.6. A knurled screw is chosen to enable the user to unfasten the laser head without the need of a screwdriver. For its positioning, the lower part of the laser fits the rectangular hole as shown in Figure 2.4. To disassemble the laser, the user needs to remove the knob and there is enough place for the laser head to be removed easily.

The SENSE has also a threading on its bottom. The SENSE is fixed to the assembly using the hole on the right of Figure 2.5. The groove on the top right is intended for the USB cable. For the positioning, three flat sides of the scanner are put against the interface piece to prevent all degrees of freedom between both objects.

Again the disassembling is made simple. The user removes the screw and then pulls on the side.

To make the assembly of Figure 2.5, a mechanical stop is used to position the interface piece of the laser. To fix them together, four holes containing a bolt are drilled in the walls of the piece in Figure 2.7.

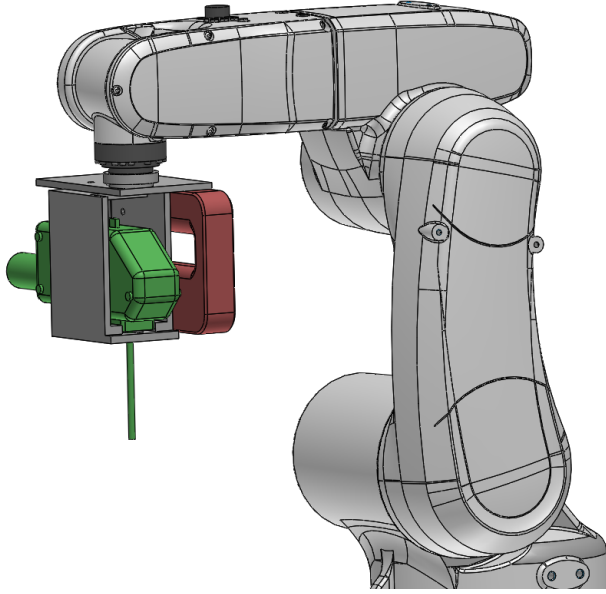


Figure 2.4: Complete assembly of the 3D scanner (green), the laser (red) and the robot

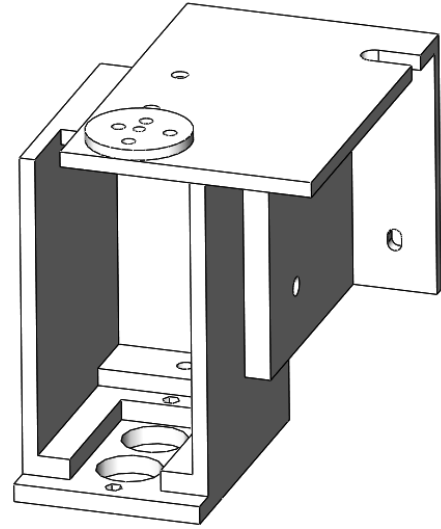


Figure 2.5: Assembly of the interface piece of the laser head and the interface piece of the SENSE

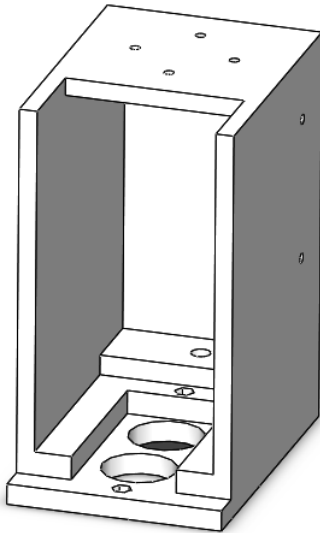


Figure 2.6: Interface piece of the laser head

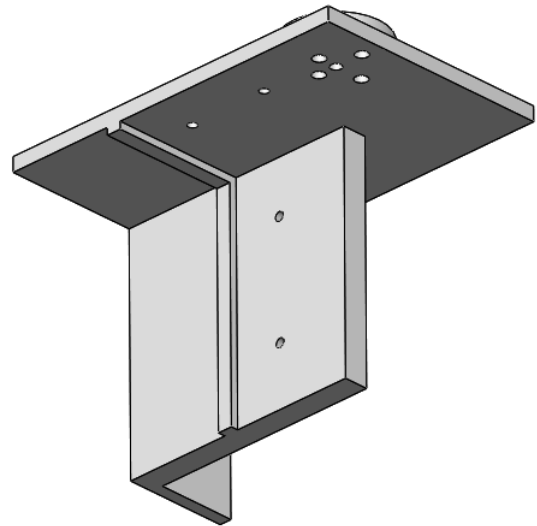


Figure 2.7: Interface piece of the SENSE

Once all 3D models are designed, it is time to print and test them with the real devices. Figure 2.8 is a picture of the complete assembly fixing the laser head and the SENSE to a robot. The robot in the picture is an Adept Viper s850 located at Saint-Luc Hospital in Brussels. It was only used to illustrate the complete solution with the laser head.

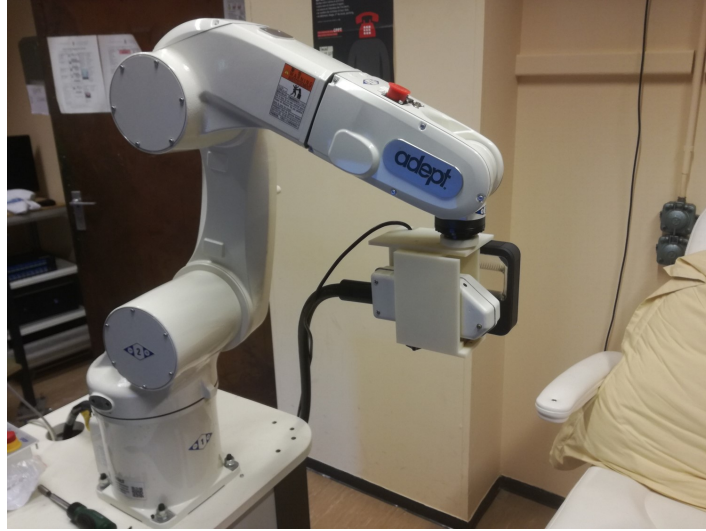


Figure 2.8: Real assembly of the solution using the SENSE 3D scanner

2.2.2 3D scan optimization

This section describes the optimal combination of parameters to be used to take the best profit of the SENSE[®] on the robot. Since the neurologist does not want to stimulate important skin irregularities, the first objective is to see if it is possible to detect them to ease his task. If it is the case, the system could detect the irregularities and could give indications to the neurologist to avoid stimulating them.

The scanner software allows to change different parameters like resolution, scanning volume, etc. To see the impact of each parameter on the scan rendering, a reference situation is imposed. The reference parameters are set to : high resolution to detect irregularities as much as possible, small scan volume since the hand and the foot have a size of about 20 cm, no object recognition, no brightness correction and track assist.

Firstly, the most appropriate distance separating the scanner from the target has to be found. In these tests, the scanner does not move during the scan. It will demonstrate if it is possible to perform a scan without having to make a movement with the robot.

Different movements with the robot are conducted above the target to see if those improve the scan rendering. If so, what is the optimal one ?

Once the optimal movement is found, the best software parameters combination needs to be determined. Each parameter is changed to see its impact on the scan quality compared to the reference situation. The details are described below.

Distance separating the scanner from the object

The first parameter is the distance separating the scanner from the object. This distance is noted D_{Sense} as in Figure 2.10.

The SENSE datasheet [36] says that the scanner does not detect anything closer than 0.2 m and further than 1.6 m. It is also advising placing the scanner at a minimal distance of 0.45m for better results.

Another element to take into account is that the area scanned is determined by the first image taken. Even if the scanner moves, it only updates points which were present in the first scene. The area of this scene depends on the field of view of the scanner which is linked to the distance between scanner and table as illustrated in Figure 2.9.

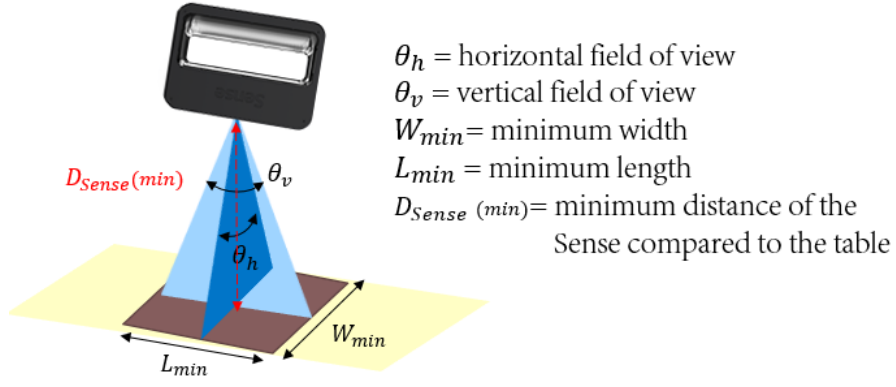


Figure 2.9: Minimum distance illustration

The specifications mentioned that the scanner must be able to see a minimum area of $30 \times 31 \text{ cm}^2$. Since the horizontal and vertical field of view of the scanner are 45° and 57.5° respectively [36], the minimum distance is found using basic trigonometry (Figure 2.9) :

$$D_{Sense(min)} = \frac{(W_{min} \text{ or } L_{min})/2}{\tan((\theta_h \text{ or } \theta_v)/2)} = \frac{(30 \text{ cm or } 31 \text{ cm})/2}{\tan((45^\circ \text{ or } 57.5^\circ)/2)} = (36.2 \text{ or } 28.2) \text{ cm}$$

The most critical case is therefore 36.2 cm which corresponds to the minimal distance to make the scan for the present application.

There is another constraint to perform scans at long distance. The robot workspace and the interface piece prevents to go above 50 cm from the table (Figure 2.10). However, it is possible to place the target below the table by rotating the robot. In the configuration of Figure 2.11, one meter is possible.



Figure 2.10: Position of the robot where the end-effector is above the table and D_{Sense} is limited to 50 cm

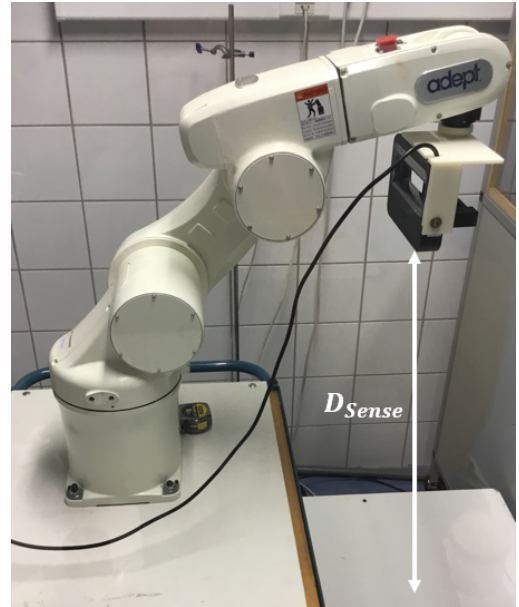


Figure 2.11: Position of the robot in order to increase the distance between the scanner and the target

Taking this into account, a first try was done with a foot prosthesis as illustrated in Figure 2.12. A scan at a distance of 35 cm gave interesting results as depicted in Figure 2.13.



Figure 2.12: Robot scanning a foot prosthesis without moving at 35cm

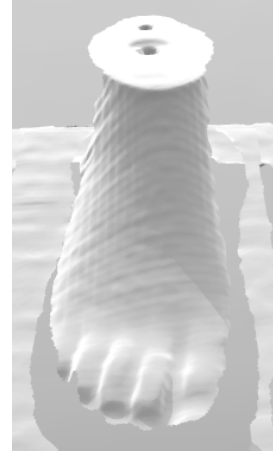


Figure 2.13: Scan of a foot prosthesis without moving at 35cm

However, after scanning a real hand, the linear pattern projected by the scanner is surprisingly visible and induces unwanted stripes as illustrates Figure 2.14. This may be due to the texture difference.

Figure 2.14 gathers the scans performed at different distances while maintaining the scanner at rest. Those where D_{Sense} is between 30 cm and 50 cm are performed in the configuration of Figure 2.10 and those with $D_{Sense} > 50$ cm as in Figure 2.11.

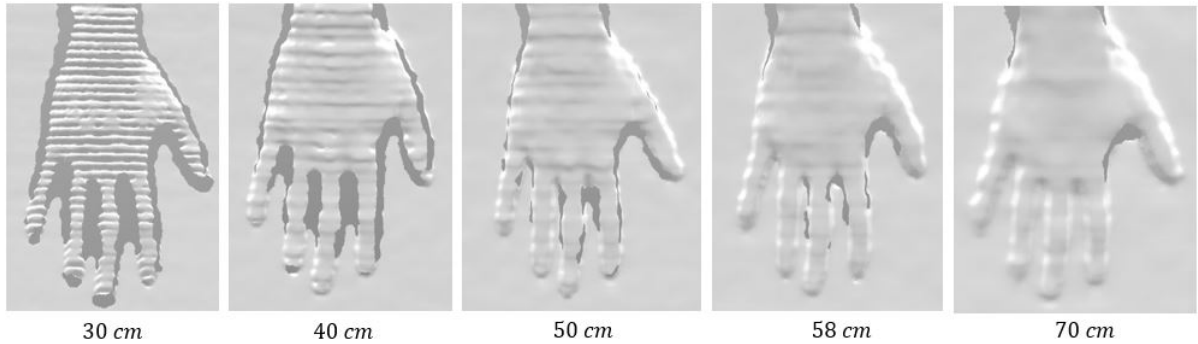


Figure 2.14: Impact of the distance from the object

Note that there is no scan at 60 cm but one at 58 cm. 'Low scanning volume' parameter is limiting the scanner to 60 cm. The scan for 70 cm is done using a 'medium scanning volume'. However, it seems not to be an optimum case since the hand has the size of a small object. We make the hypothesis that the 'low scanning volume' parameter is the best case and we will verify it later.

The induced stripes of the scan are decreasing as D_{Sense} is increasing. The stripes on the scan at 58 cm give an error angle under the maximum error of 15° . This scan using only one shot can therefore meet the requirements. However, it is obviously not the best result that can be obtain with the SENSE. Other scans will be performed to improve the data.

In order to check if the scanner is able to detect skin irregularities, movement above the sense are performed to decrease the stripes.

Movements of the scanner above the target at 50 cm

For the next tests, the goal is to observe the impact of the movement on the stripes at a height of 50 cm.

The lines of the pattern are directed along the X -axis. Since the camera of the scanner is supposed to observe the deformations of these lines, performing a movement along the X -axis with the robot would not be useful. Indeed, as represented in Figure 2.15, a movement along the Y -axis is better since the movement is perpendicular to the direction of the pattern lines. A combination of the translation along Y and rotation along X gives an even better result.

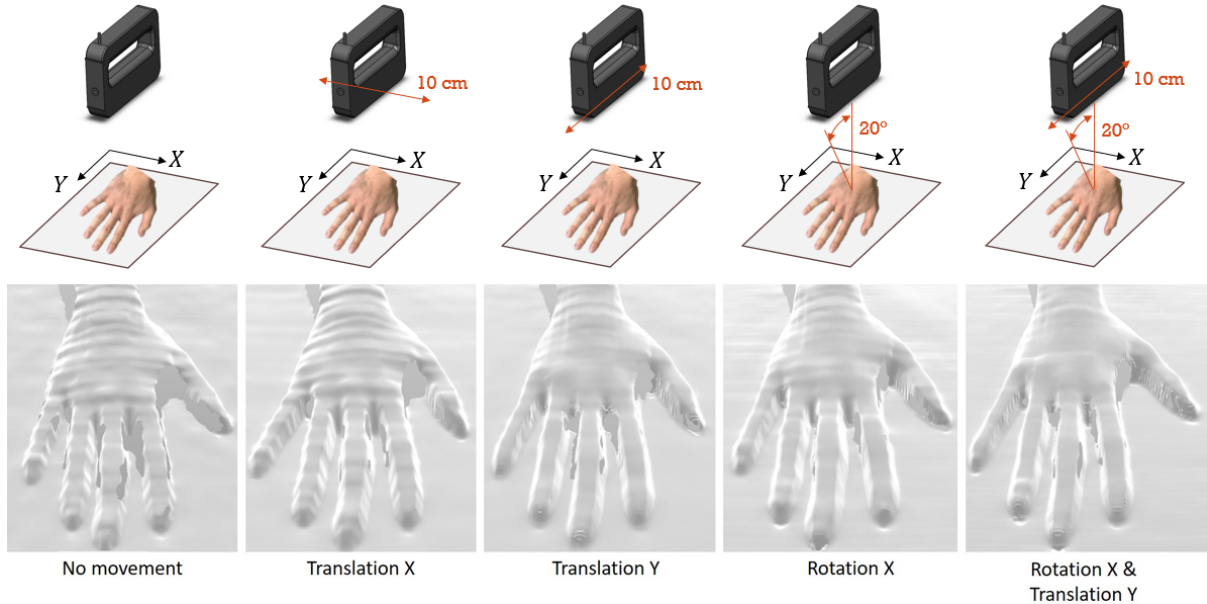


Figure 2.15: Movements of the robot end-effector performed above the target

Since the X-Y movement smoothed all stripes at 50 cm, is it also the case at 40 cm ? By being closer, we expect to detect better skin surface. However, we are more sensitive concerning stripes.



Figure 2.16: Scan at 40 cm with a movement of rotation and translation

Figure 2.16 shows that the stripes do not completely disappear. The distance of 50 cm will be kept for the next trials.

Since a solution for removing stripes at 50 cm has been found, our next goal is to see if the scanner is able to detect irregularities on a human hand. To do so, we scanned a hand with the tendons exaggerated as presented in Figure 2.17. The irregularity height is approximately 4 mm which is a situation that should not appear normally in practice. This choice is motivated by the fact that a real hand must be used to have the right texture.

At this stage, placing the scanner at 50 cm and performing a specific movement, the scanner smooths too much the surface to identify the irregularities as it can be seen in Figure 2.17.



Figure 2.17: Scan at 50 cm with a movement of rotation and translation trying to detect skin irregularities

Optimization of software parameters

The goal of this paragraph is to explain how to improve software parameters to be able to detect skin irregularities.

The situation of reference is the following : high resolution, small scan volume, without object recognition, with brightness correction and with track assist. There are thus 5 parameters to analyze separately. The end goal is to determine if, with the maximum capabilities of the scanner, it is possible to detect the skin surface irregularities. As a reminder, the scan is performed at a distance of 50 cm with a movement combining a rotation and a translation.

1. Resolution :

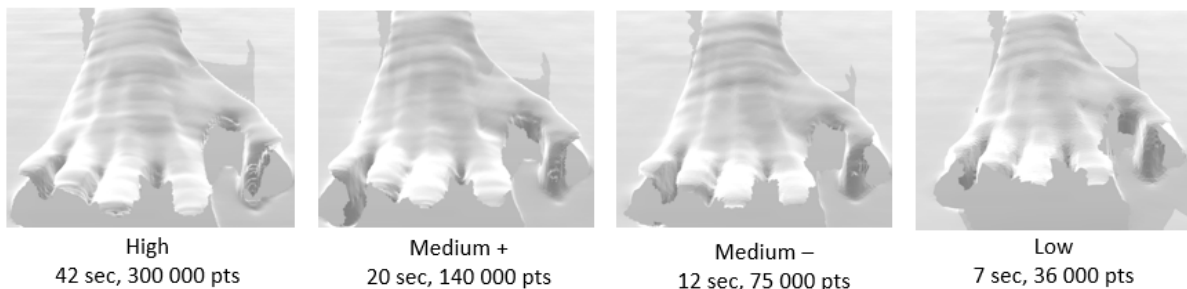


Figure 2.18: Influence of the resolution

As expected, the irregularities are less seen when the resolution decreases. However, the general shape of the hand remains correct. In addition, the software processing time and the number of points used in the 3D model decrease with the resolution. Regarding the number of points, a factor 10 is observed between high and low resolutions.

Two scenarios are possible. The first one is to continue to use high resolution to determine if it is possible to detect irregularities that could then be avoided by the robot.

The second one is to use a low resolution and ignore the irregularities. In this case, the neurologist must avoid irregularities by himself.

As mentioned before, the result of the scan without movement at 58 cm still contains small stripes. Using a low resolution should decrease them.

2. Volume :

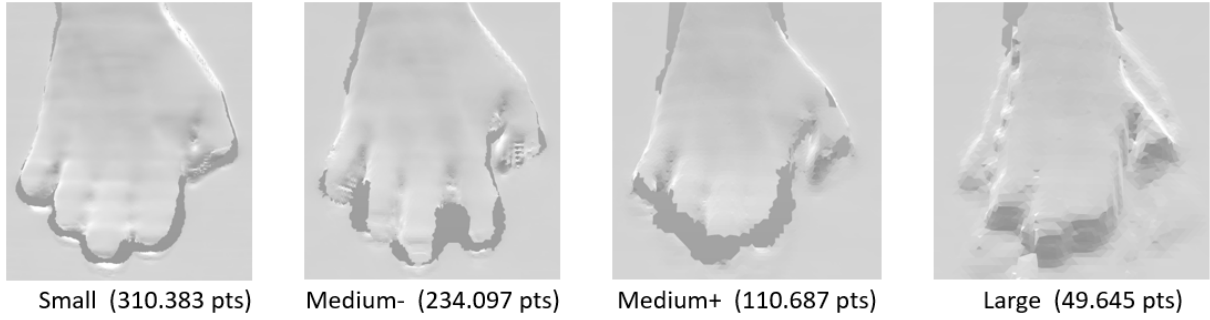


Figure 2.19: Influence of the scanning volume at high resolution

As the scanning volume increases, the software is using fewer points for a fixed resolution (high resolution here). It results in a smoothed hand as in Figure 2.19.

The hand being small compared to the capability of the scanner (up to $2 \times 2 \times 2 \text{ m}^3$ [36]), increasing the scanning volume is not relevant. The resolution should be the parameter to adjust if the goal is to smooth the hand and ignoring the irregularities.

Moreover, if the volume increases, the scanner detects something outside the table like in Figure 2.20. It will then pollute the next computations.



Figure 2.20: Complete 3D model for large scanning volume

A small volume is therefore used.

3. Object recognition, brightness correction and track assist :

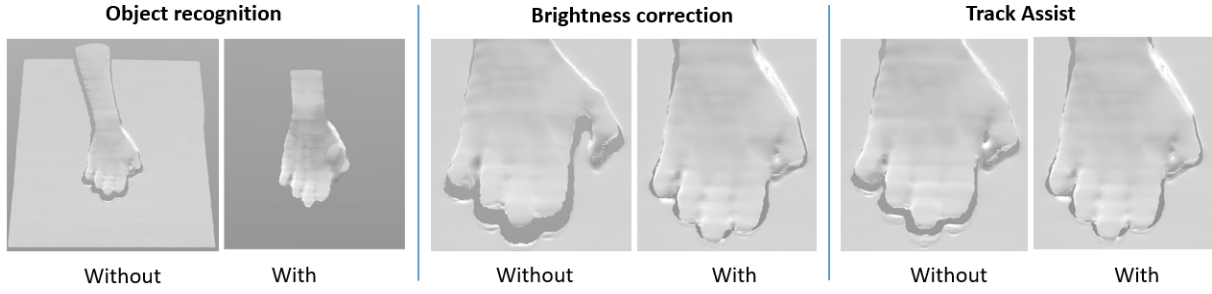


Figure 2.21: Influence of object recognition, brightness correction and track assist

The object recognition parameter must not be activated otherwise the table under the hand is not detected as depicted in Figure 2.21. As it will be presented in Section 2.2.3 regarding the data processing, the table is important. Indeed, it allows to replace the hand in the robot frame.

Finally, brightness correction and track assist are not enhancing the scan quality.

Summary

As a conclusion, the SENSE is not able to fully capture the irregularities on a human hand. However, it is able to obtain the general shape of the hand very clearly. There are two options allowing to capture the shape of hand or foot ignoring the irregularities. Ignoring the irregularities allows to use a lower resolution. Therefore, there is a smaller number of points, which considerably decreases the time needed for the next computations.

The first option is to make a scan without moving at a height of 58 cm. The second one is to make a movement with the robot at a height of 50 cm. The movement is a combination of a rotation around the 'X' axis and a translation along the 'Y' axis. For both techniques, the software parameters are the same : low resolution and a small scanning volume. The object recognition is not activated but the brightness correction and the track up assist are.

The advantage of the first option is that the robot does not make any movement. This way, it does not waste time whereas the second solution takes approximately 20 seconds to realize the complete movement.

Figure 2.22 summarizes both options. The second one gives a better result.

The time to make a scan is crucial because, if the patient moves during the experiment, the scan needs to be performed again to update the scene. Both solutions contain the same number of points so they will take the same time regarding the computational time. Since the time taken by the movement is of only 20 seconds, the second option is kept. Moreover, the scan rendering is better.

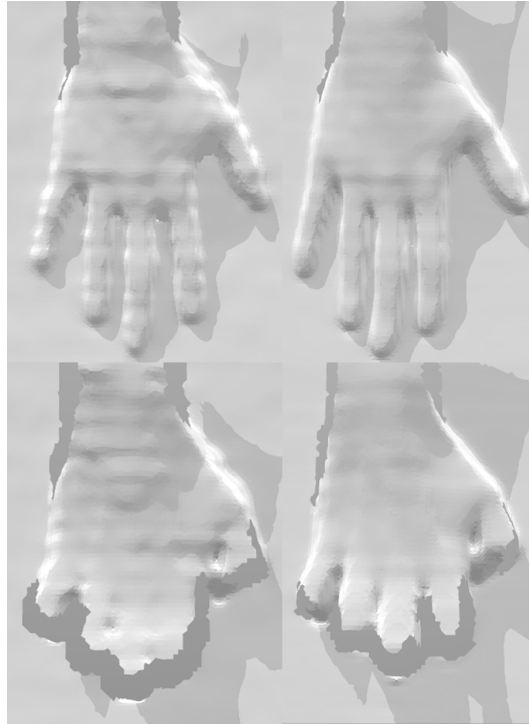


Figure 2.22: Comparison between the scan with no movement at 58 cm (on the left) and the scan with a movement at 50 cm (on the right)

Finally, the optimal situation is summarized in Figure 2.23.

- $D_{Sense} = 50$ cm
- Movement : rotation along X & translation along Y
- Software parameters :
 - Low resolution
 - Small scanning volume
 - Without object recognition
 - With brightness correction
 - With track assist

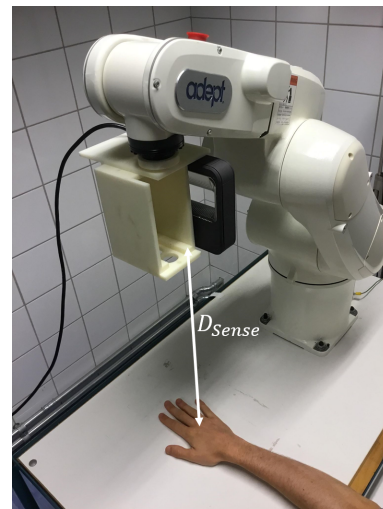


Figure 2.23: Optimal situation

2.2.3 Data processing

Now that scans are of good quality, it is needed to compute the position where the laser head needs to be placed by the robot given the 3D model provided.

Figure 2.24 shows the raw point cloud of a scan performed with the robot placed in the situation of Figure 2.25. The plane of the table is perpendicular to the ‘Y’ axis since the robot places correctly the device at the beginning of the scan.

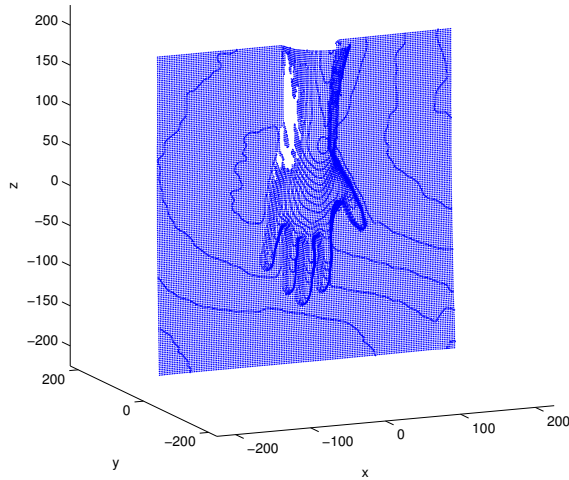


Figure 2.24: Raw point cloud of a scan performed with the robot

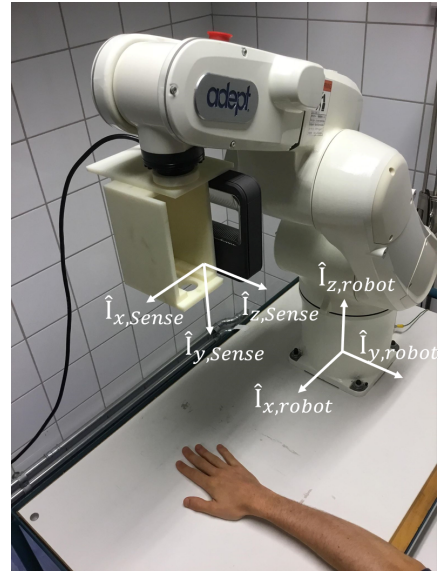


Figure 2.25: Robot frame and the SENSE

Transformation in the robot frame

In Figure 2.24, the coordinates of the points are still expressed in the scanner frame instead of the robot frame. Figure 2.25 highlights the link between those frames. To convert from one to the other, a 90° rotation around the ‘X’ axis is needed.

When the transformation is applied, the model seems to be in the correct frame as depicted in Figure 2.26. However, Figure 2.27 shows that it is not completely horizontal. This can be due to a small misalignment between the robot and the table.

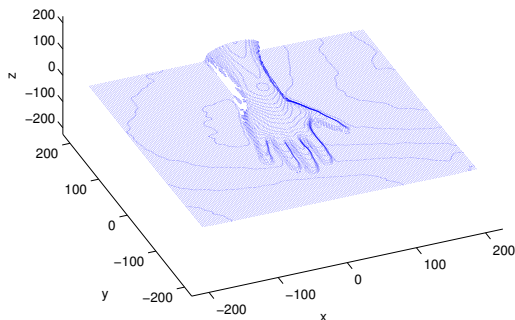


Figure 2.26: Rotated point cloud of a scan performed by the robot

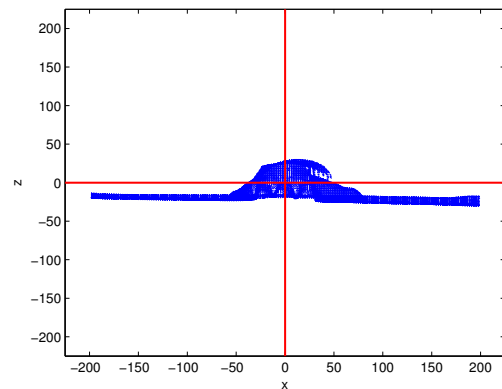


Figure 2.27: Lateral view of the point cloud rotated

Another problem that was previously described in Section 1.3 is that the zero coordinate of the point cloud is located in the center of the scan. It means that the scan is not yet expressed in the robot frame.

The goal is to locate hand or foot in the robot frame so that the robot knows where to position the laser compared to the skin.

The coordinates of the points only depend on the size of the object itself and does not have any relation with the environment around it.

One way to know the location and the orientation of the scan is to identify some parts inside the scan corresponding to the real world. By knowing the location of these parts compared to the robot, it is possible to express the point coordinates in the robot frame.

To perform this task, a plate is placed on the table as illustrated in Figure 2.28. To position precisely this green plate compared to the robot, another piece is used. This piece in brown is built using a laser cutter to obtain a high accuracy.

Figure 2.29 represents the scan of a hand placed on the green plate. The edges of the plate are clearly visible. By knowing the position of these edges in the robot frame and in the scanner frame, it is possible to compute the transformation that the point cloud must undergo to be expressed in the robot frame.

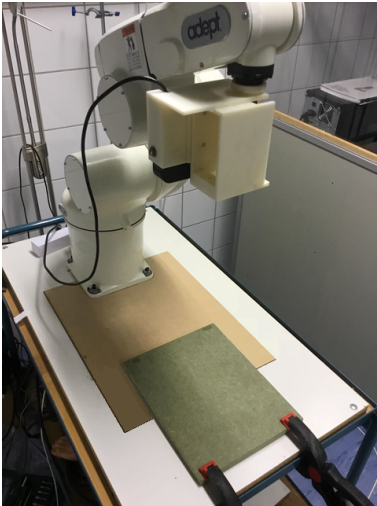


Figure 2.28: System to position a plate precisely in the robot frame

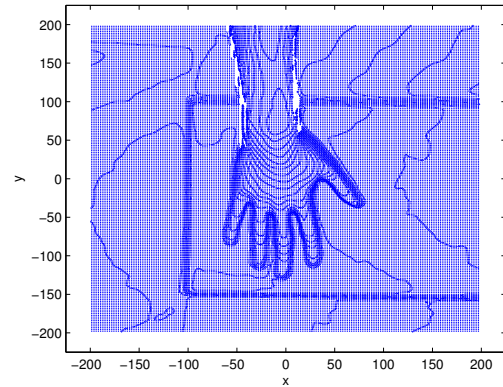


Figure 2.29: Top view of the point cloud of the scan using a plate

The results are the following. The scan frame must rotate of -0.025° around the 'X' axis, of -1.283° around the 'Y' axis and of 0.807° around the 'Z' axis.

Concerning the translation that the points must undergo, the left side of the plate is at +350 mm of the robot center along 'X' and the plate is centered in the 'Y' direction. In the scan represented in Figure 2.29, the left side of the plate is at -95 mm in 'X' and the plate is centered in -26.5 mm along 'Y'. Thus, each point must be shifted of +445 mm along the 'X' axis and of +26.5 mm along the 'Y' axis.

All these transformations will be the same for every scan. Indeed, the frame and the edges of the scan are determined by the first image taken. This image is always the same since it is the robot that positions the scanner.

The only transformation changing for every scan is the offset along the 'Z' axis since every patient has a different hand or foot. Thus, the height of the complete model and its center also

changes between two scans. A constant shift along the ‘Z’ direction cannot be applied. However, the surface of the table is present in the scan and corresponds to the XY plane of the robot frame ($z = 0$). Therefore, the whole model is lowered by the ‘z’ value of the points belonging to the table in the point cloud.

In the end, the same point cloud is obtained but expressed in the robot frame as shown in Figure 2.30. Now, the robot knows where the hand or the foot is located.

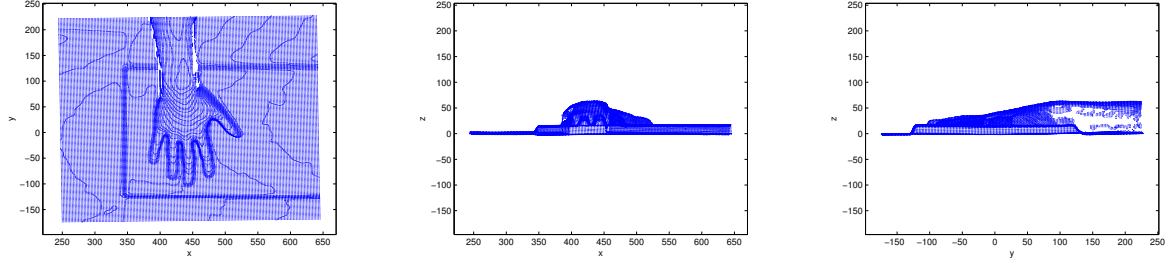


Figure 2.30: Point cloud of the scan using a plate in the robot frame : top view, front view and lateral view

Points organization

Once the scan is in the right frame, the point cloud is organized to easily work with it. The objective is to get the ‘Z’ component of a point by knowing its ‘X’ and ‘Y’ components.

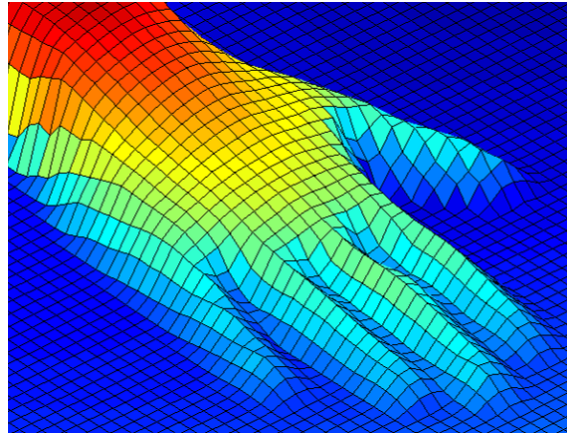


Figure 2.31: Mesh of the scan using a step of 5mm and a radius of 5mm

To obtain the result in Figure 2.31, the technique is to create a grid with a defined step. Each line crossing corresponds to one point and, for each of them, its ‘Z’ component has to be determined. The technique is to take all points at proximity of the point of interest that are closer than a certain predefined radius. Then, the mean of the ‘Z’ component of these points is computed and assigned to the ‘Z’ component of the point of interest.

Two parameters can be changed. The first one is the step between the lines of the grid. Figure 2.32 shows the mesh using a step of 2 mm. It follows the shape of the hand, but the number of points is significantly bigger. This means that the computational time increases. To organize the points, it takes approximately 58 seconds for a step of 2 mm, 13 seconds for a step of 5 mm and 6.5 seconds for a step of 10 mm. Figure 2.33 shows the mesh with a step of 10 mm. Here, the number of points is low but the shape of the hand is too simplified to be used.

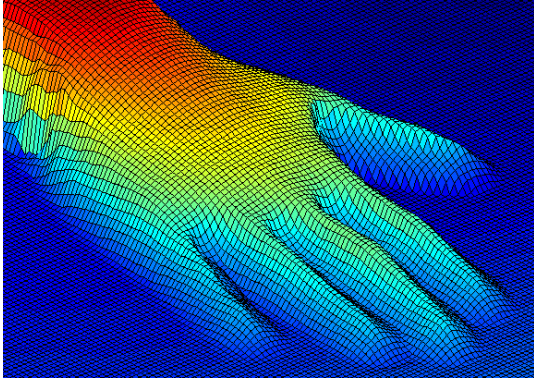


Figure 2.32: Mesh of the scan using a step of 2 mm and radius of 5 mm

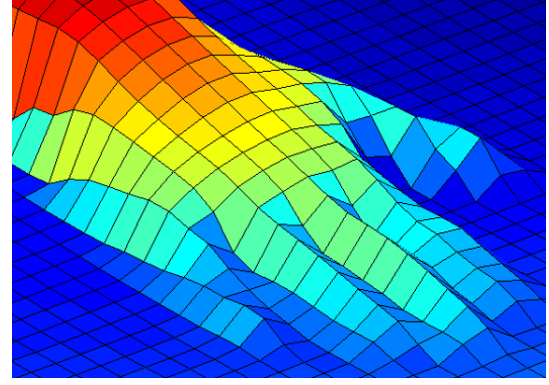


Figure 2.33: Mesh of the scan using a step of 10 mm and radius of 5 mm

The second parameter is the radius determining the number of points taken to compute the mean of the 'Z' component. On the one hand, if the radius is too small, there might be no point of the model inside it, causing problems as illustrated in Figure 2.34. On the other hand, if the radius is too important, the surface is too smoothed. For instance, Figure 2.35 shows that the edges of the hand are not straight, especially for the fingers.

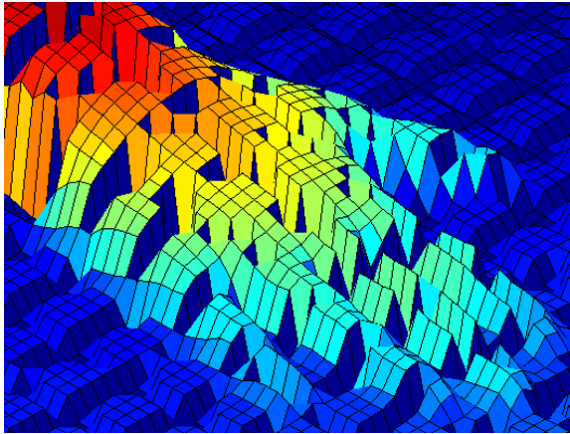


Figure 2.34: Mesh of the scan using a step of 5 mm and radius of 1 mm

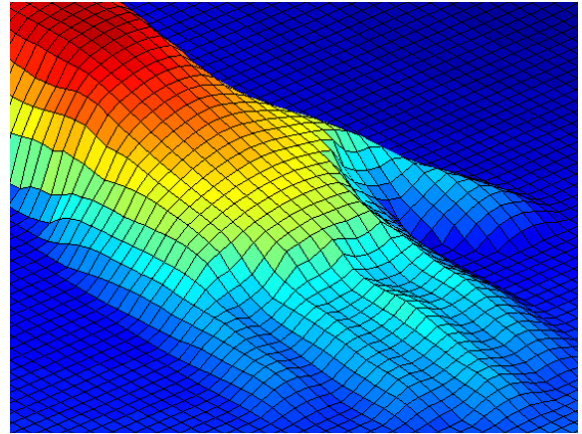


Figure 2.35: Mesh of the scan using a step of 5 mm and radius of 10 mm

At the end, a step of 5 mm and a radius of 5 mm seem to be a good compromise as shown previously in Figure 2.31

Position computations

Now, the 3D model is easy to work with and is expressed in the robot frame. The final step is the determination of the correction to apply on the robot positioning to place the laser correctly compared to the skin surface.

The first objective is to find the normal of the skin surface aimed by the laser beam. To find the points of the 3D model aimed by the laser beam, the information given by the robot is useful. Indeed, since the robot is equipped with precise encoders, it can retrieve the position and orientation of the laser head. By knowing this information, the equation of the emission line of the laser is computed. Then, the points the closer to this line have to be found. Three points are sufficient to find the plane going through the targeted surface. To do so, the position of these points are noted O^1 , O^2 and O^3 .

To find the normal of this plane, the vector linking O^1 to O^2 noted $\mathbf{o}^{12}$ and the vector linking O^1 to O^3 noted $\mathbf{o}^{13}$ are computed.

$$\mathbf{o}^{12} = O^2 - O^1 \quad \mathbf{o}^{13} = O^3 - O^1$$

A vector parallel to the normal of the plane is found by making the cross product between $\mathbf{o}^{12}$ and $\mathbf{o}^{13}$. Then, the result is normed to find the normal of the approximated plane noted $\mathbf{n}$.

$$\mathbf{n} = \frac{\mathbf{o}^{12} \times \mathbf{o}^{13}}{\|\mathbf{o}^{12} \times \mathbf{o}^{13}\|}$$

The equation of the approximated plane, noted Π , is therefore the following :

$$\Pi \equiv n_1x + n_2y + n_3z + C = 0$$

where n_1 , n_2 and n_3 are the three components of $\mathbf{n}$ and C is a constant to determine. The coordinates (x, y, z) are changed by the coordinates of a point belonging to the plane Π , for example, O^1 . This gives :

$$C = -n_1O_1^1 - n_2O_2^1 - n_3O_3^1$$

And the equation of the plane becomes :

$$\Pi \equiv n_1x + n_2y + n_3z - n_1O_1^1 - n_2O_2^1 - n_3O_3^1 = 0$$

The next step is to find the coordinates of the point that the laser head is targeting. Since the laser line is aligned with the Z axis, the components of the central targeted point are $(0, 0, O_3^C)$. By injecting these coordinates in the expression above, it gives :

$$O_3^C = \frac{n_1O_1^1 + n_2O_2^1 + n_3O_3^1}{n_3}$$

It is possible to determine the position where the laser origin should be placed. This point is noted O^F .

$$O^F = O^C + 100 \mathbf{n}$$

where the factor 100 corresponds to the 100 mm separating the target. All quantities in the previous computations are expressed in millimeters.

Finally, this information could then be converted into a movement instruction for a robot.

2.3 Distance sensors implementation

This section begins by characterizing the sensor behavior and compare it to the datasheet [37]. Using this information, the mechanical interface is designed. Once all sensors are fixed to the robot end-effector thanks to the interface, their behavior is verified when operating together. The function giving the distance of detection based on the ARDUINO output is found and these measurements are used to compute the correct position of the laser.

2.3.1 Sensor characterization

In order to use the SHARP sensor in the final solution, its behavior is characterized. Firstly, a sufficiently constant output is obtained by decreasing the measurement noise. Then, the sensors characteristics are compared to the datasheet [37]. Finally, since the system composed of three distance sensors measures angles, the impact of a tilted surface on the sensor measurements is quantified.

Noise cancellation

Figure 2.36 presents in blue the raw data given by the SHARP sensor when facing a white wall at a fixed distance during 10 seconds. Here, the ARDUINO output is used and two values are repeating more than the others. Our hypothesis is that the correct value should lie between these two values. The weighted average of these two values is :

$$\text{Weighted value} = \frac{V_1 \cdot n_1 + V_2 \cdot n_2}{n_1 + n_2}$$

where V_1 and V_2 are the most two appearing values. They appear n_1 and n_2 times respectively. The weighted average is calculated using a total of 100 measurements. The first reason is because 100 values are enough to obtain a constant output as shows Figure 2.36 where the red dots correspond to the weighted average. The second reason is because using only 100 values makes the program run fast. The measurement are thus quickly updated. This update is important since the time between two stimulations of the laser is limited.

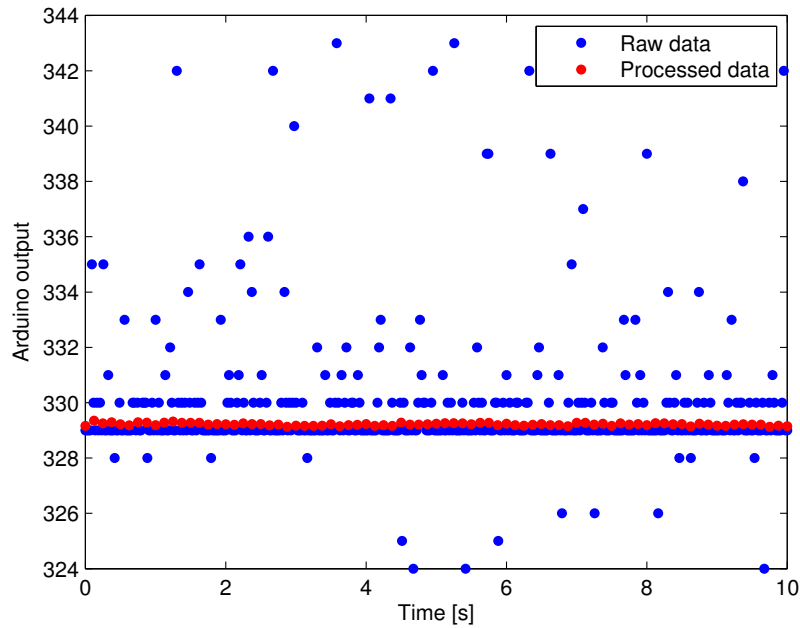


Figure 2.36: SHARP raw data and weighted average value over 100 measurements

Sensor characteristic

As the output is stable over time, it is possible to determine at which distance it corresponds. To do so, the sensor is fixed on a measuring column which is able to measure a distance with a resolution of 0.01 mm. Measurements are done from 0 mm to 200 mm with a step of 5 mm. Figure 2.37 illustrates the experiment and Figure 2.38 presents the results corresponding to the characteristic of each sensor.



Figure 2.37: SHARP fixed to a measuring column

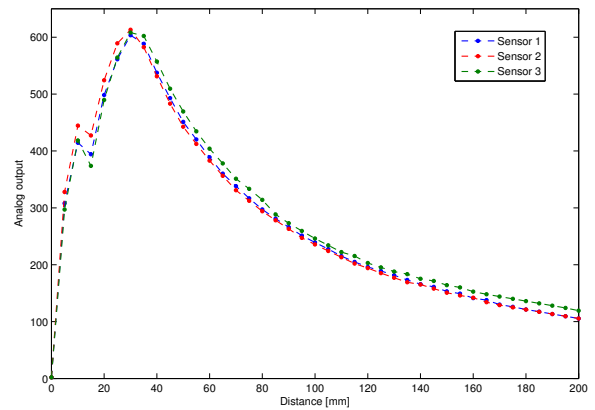


Figure 2.38: Sensors characteristic between 0 and 200 mm

All characteristics are similar but not completely identical. If the ARDUINO output is changed in voltage thanks to the conversion explained before, a similar characteristic as the datasheet example [37] is obtained.

Influence of the angle on the distance measurements

Is the sensor behavior affected when targeting a tilted surface ? To carry this experiment, the sensor line emission is identified. Indeed, it is important to rotate along a point belonging to this line in order to keep the distance measured by the sensor. In addition, knowing the location of the emission line will be useful for the mechanical interface design.

The laser line emission of the SHARP distance sensor is identified with the procedure illustrated in Figure 2.39. A small cylinder is translated along a fixed distance while observing the sensor output. According to the sensors characteristics, the output decreases if the distance increases and inversely. It is therefore possible to know when the sensor is detecting the cylinder. Its output should progressively increase as the cylinder enters in its field of view and then decrease when it goes out from it. By repeating the same operation for different distances, the line emission of the sensor is drawn. In conclusion, this line is perpendicular to the sensor and located in the emitter center.

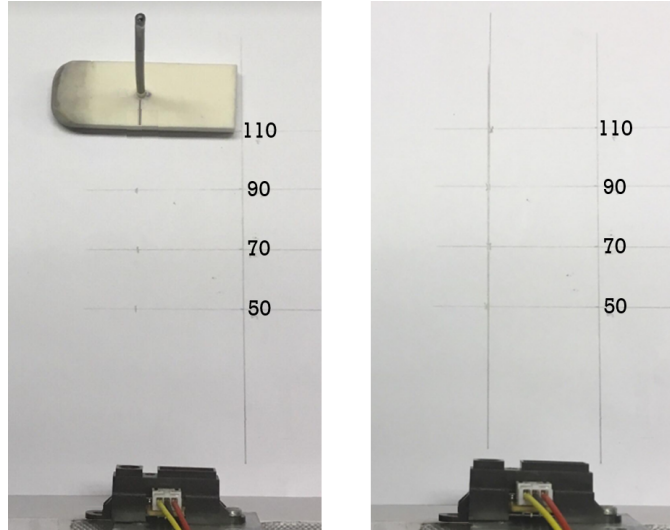


Figure 2.39: Theoretical solution using three distance sensors

Knowing the line emission of the sensor, the influence of the angle of the target on the measurements is studied. To do so, a vertical plane is placed in front of the sensor n°1 distant from 70 mm. The plane is positioned in different orientations varying from -50° to 50° .

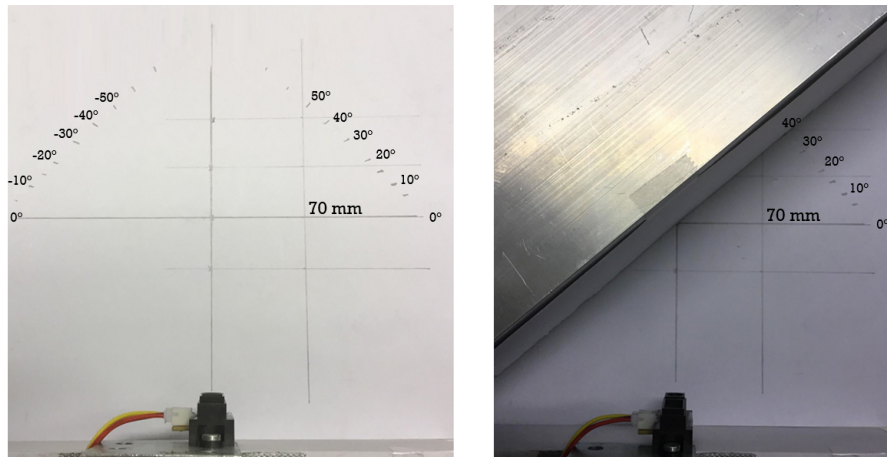


Figure 2.40: Situation where the distance sensor is placed vertically. The angle varies from -50° to 50°

The measurements of the sensor are recorded. The same operation is done for the sensor placed horizontally and vertically. The results are illustrated in Figures 2.41 and 2.42. The values generated by the sensor have a maximal variation of 4 in the horizontal and vertical cases compared to the reference of 0° . According to the characteristic of sensor n°1, the distance is varying of approximately 1 mm. This slight variation is not negligible. However, it is not possible to compensate it since it is random.

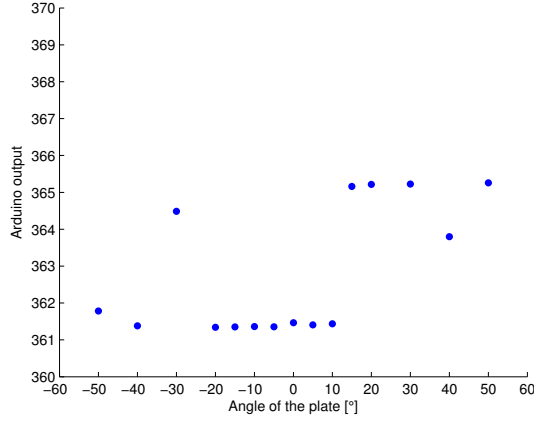


Figure 2.41: Measurements variation when facing a tilted surface while placing the sensor horizontally

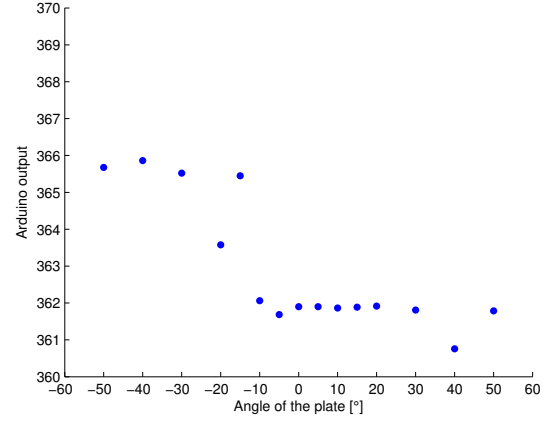


Figure 2.42: Measurements variation when facing a tilted surface while placing the sensor vertically

2.3.2 Mechanical interface

This section details the function of the mechanical interface linking the sensors to the laser head and the constraints that it has to deal with.

In Section 1.3, theoretical design for the assembly of the sensors was already proposed. This design is shown in Figure 2.43.

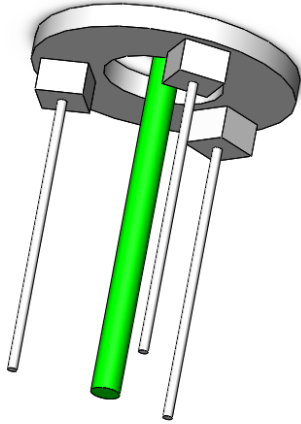


Figure 2.43: Theoretical solution using three distance sensors

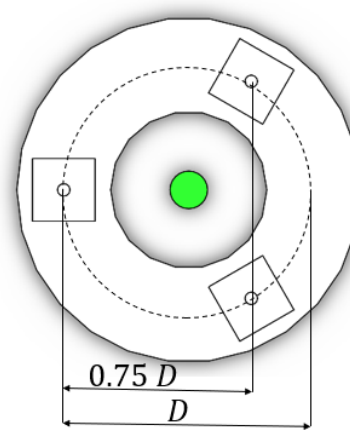


Figure 2.44: Bottom view of the theoretical solution using three distance sensors

Unfortunately, this design is not applicable for different technical reasons. First, in this design, the sensors are too close to each other. The hole where the laser beam passes through has a diameter of 25 mm. Therefore, since the sensor has a certain width, the distance between the origin of the sensors line emission has to be wider than 25 mm. Then, the laser head comprises another hole used to measure the distance from the target. Nothing can obstruct its field of view. Therefore, our first idea of placing one distance sensor every 120° as in Figure 2.44 is not valid.

Figures 2.45 and 2.46 show the solution found to deal with these constraints. The distance between the sensors is large enough to not obstruct the hole for the laser. The three sensors are placed on three edges of a rectangle to not obstruct the second hole.

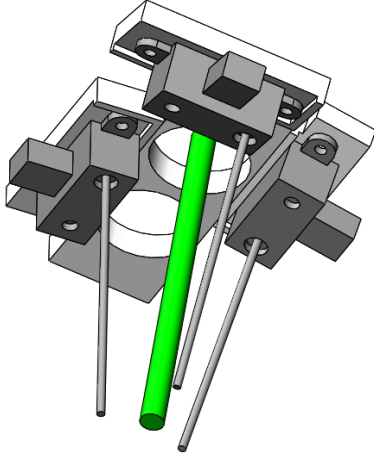


Figure 2.45: Solution of the system using three distance sensors

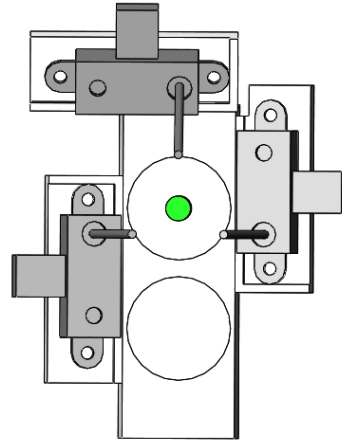


Figure 2.46: Bottom view of the system using three distance sensors

Section 1.3 demonstrated that the points on the skin surface measured by the sensors have to be on a circle of 25 mm diameter. In addition, the center of this circle must correspond to the laser beam as in Figure 2.44. However, with this new design, it is only possible for a unique distance. Our choice is to set this distance to the middle of the laser range, namely 100 mm. At this distance, 3 points are precisely located on a circle of 25 mm diameter as Figure 2.46 shows. Figures 2.47 and 2.48 show respectively the position of those 3 points for a distance between the laser and the skin of 85 mm and 115 mm respectively. The distance between the points changes. Thus, the impact of a measuring error on the angle will also change. But is not a big deal. Indeed, the measurements of the sensors continuously tell the robot to reposition itself such that the skin is 100 mm away from the laser origin.

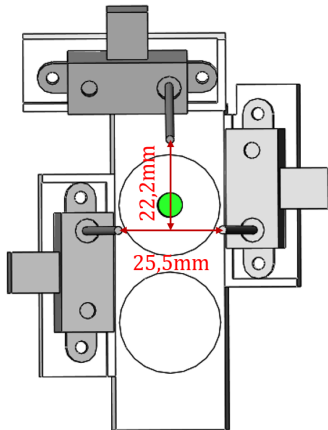


Figure 2.47: Bottom view of the system using three distance sensors showing the space between the points of measurements when the laser is at 85 mm from the skin

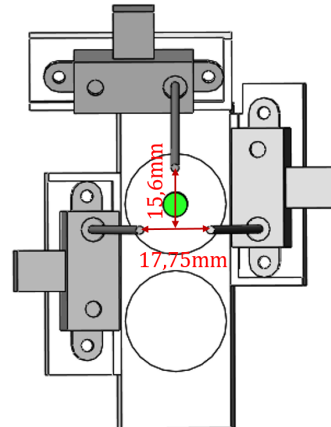


Figure 2.48: Bottom view of the system using three distance sensors showing the space between the points of measurements when the laser is at 115 mm from the skin

The sensors are slightly tilted. These small angles caused some difficulties to 3D print this part. Indeed, since the layers of the 3D printer has a certain thickness, it is difficult to obtain a smooth surface for slightly tilted surfaces. To deal with this problem, the piece was printed flat on the table such that the walls are perfectly vertical. The bottom layer is linking all parts of the piece together allowing to keep their precise positioning as illustrated on the right in Figure

2.49. Openings between the central and the external parts offer a specific spacing. It then allows to tilt and glue the external parts against the central one.

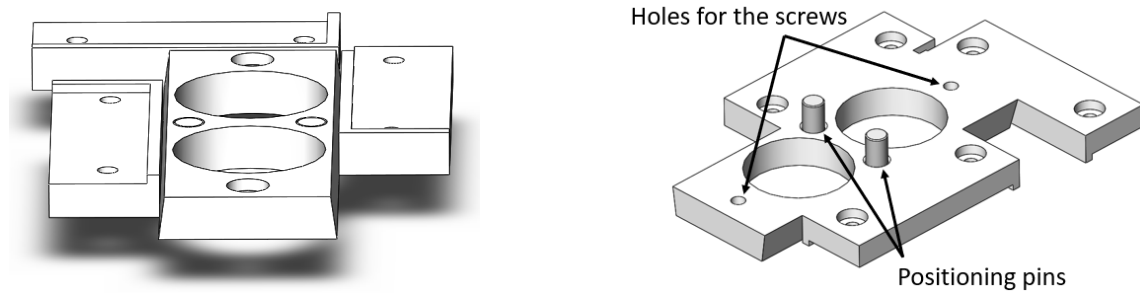


Figure 2.49: 3D model of the piece assembling the three distance sensors

The system of three sensors has to be fixed on the laser head. Since an interface was already designed to fix the laser head to the robot, this same interface is used to fix the system of three sensors below the laser origin. Two pins are added for the positioning and two screws to fix them together. Their positions are visible on the right in Figure 2.49.

In the end, the complete system using distance sensors is in Figure 2.50. Remark that an additional piece needs to be designed to fix this assembly to the robot. Four holes are present on the top of the piece for this function.

For now, it is more practical to use the mechanical interface of the SENSE. In this way, both solutions could be tested separately without having to remove them each time from the assembly. This assembly, represented in Figure 2.51, could also be useful in the case of a combination of both systems.

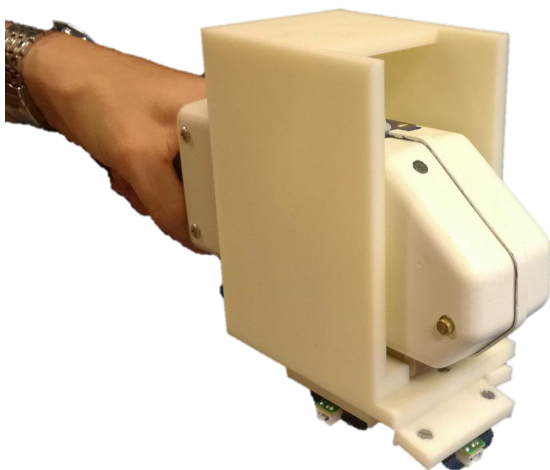


Figure 2.50: Complete assembly of the system using three distance sensors. An additional piece needs to be designed to fix this assembly to something else.

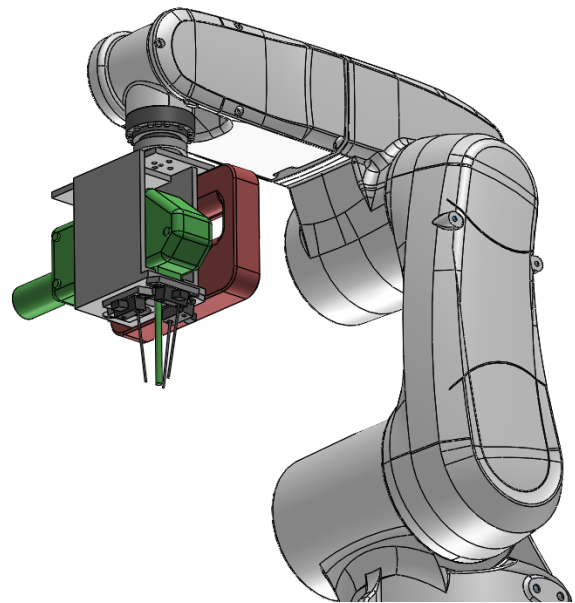


Figure 2.51: Complete assembly of the system using a 3D scanner and the system using three distance sensors

Measurements using the whole system

Since the sensors are now giving a stable distance, they are assembled and fixed to the robot. Figure 2.52 shows the measurements recorded for all sensors for 10 seconds for three situations. On the left, all sensors are activated together with the same ARDUINO supply PIN. In the center, the graph shows the superposition of three recordings where only one sensor is supplied. The last situation is when the sensors are all supplied but one at a time.

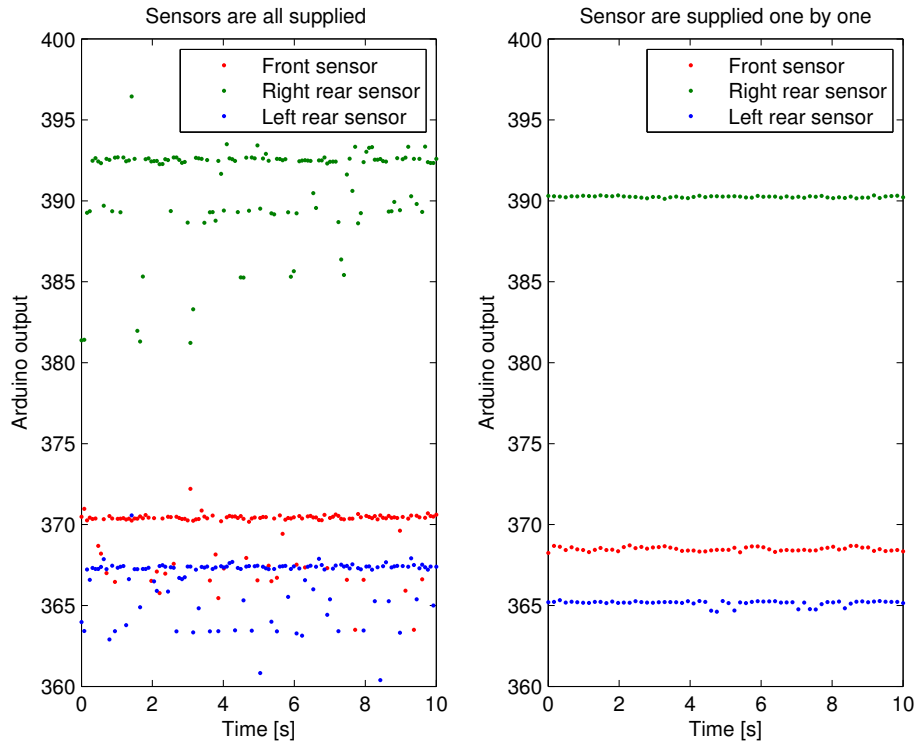


Figure 2.52: Illustration of the sensors interferences

The measurements have important oscillations when supplied together. This could be due to interferences between the different sensors. Indeed, since they are all measuring distances at the same time. A signal emitted from one sensor could have been detected by the receptor of another and therefore disturbing the result. To solve this problem, the supply pin of each sensor is connected to a different digital pin of the ARDUINO. It allows to supply them one by one. For example, the front sensor is turned on, collects some measurements and then is turned off. Next, the same procedure is performed for the right rear sensor and finally for the left rear one. In this way, sensors are not interfering the measurements of the others. However, to realize this sequence, certain delay before the switching has to be artificially introduced because the sensor takes some time to start and stop measuring. A minimum delay of 20 ms is required. This delay is thus introduced each time a sensor is switched on and off giving a total delay of 120 ms. The graph on the right has fewer points but constant measurements.

Finally, the system of three sensors quickly provides a new measurement even if it is needed to turn them on and off for each cycle. The potential movement of the patient could still be taken into account.

2.3.3 Distance evaluation

The next objective is to find the function that takes in input the data given by the ARDUINO and that gives in output the distance between the object and the sensor.

The characteristic of all sensors are recalled in Figure 2.53.

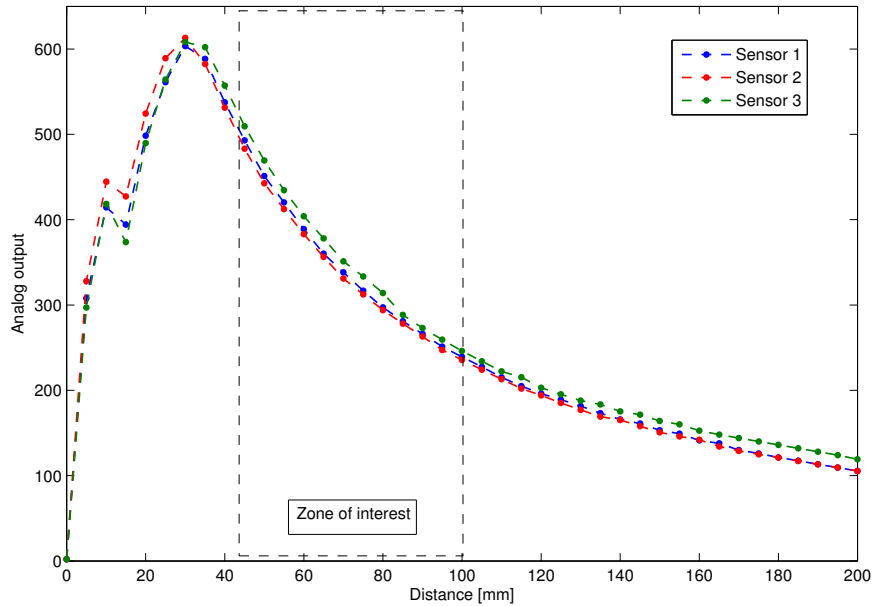


Figure 2.53: Transfer function of SHARP sensors

Our goal is that the approximation has to be the most accurate in a range where the distance sensors will be the most used. Indeed, the laser is working between 85 and 115 mm apart from the skin surface. As depicted in Figure 2.54, the sensors are not at the same level as the laser.

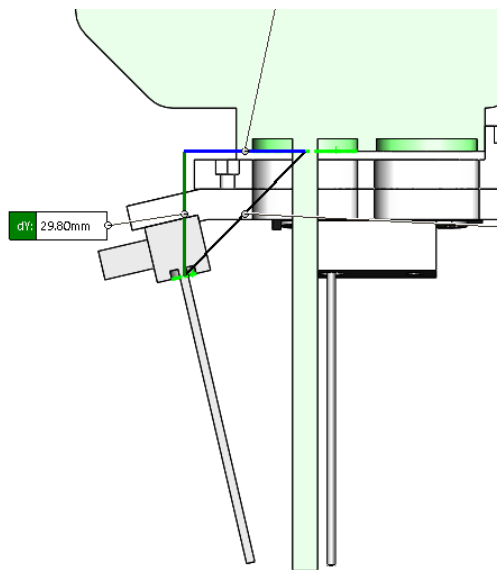


Figure 2.54: Cross-sectional view of the system using three distance sensors showing that the front sensor is below the laser origin

The front sensor and the rear sensors are placed respectively 29.8 mm and 29.21 mm below the laser origin. In addition, they are respectively tilted at an angle of 13.13° and 7.67°. A laser range of 50 mm is chosen instead of 30 mm because the sensors can detect further or closer when the whole system is tilted.

The front sensor will be therefore mostly used in the following range :

$$\begin{aligned} \text{Lower bound : } \frac{75 - 29.8}{\cos(13.13^\circ)} &= 46.41 \text{ mm} \\ \text{Upper bound : } \frac{125 - 29.8}{\cos(13.13^\circ)} &= 97.76 \text{ mm} \end{aligned}$$

Doing the same for the rear sensors, the zones of interest are [46.41 mm - 97.76 mm] for the front and [46.20 mm - 96.65 mm] for the rear. The approximation of the transfer function needs to be the most accurate in the range [45 mm - 100 mm] which is the zone of interest drawn in Figure 2.53. Only the points that are in the zone of interest will be used for the next computations.

To approximate the transfer functions in this particular range, two methods are possible :

1. The sensor datasheet proposes a relation using the inverse of the distance [37]. Figure 2.55 shows that it almost makes a straight line. Note that the factor 10 for the X-axis expression is used to convert the distance from millimeters to centimeters.

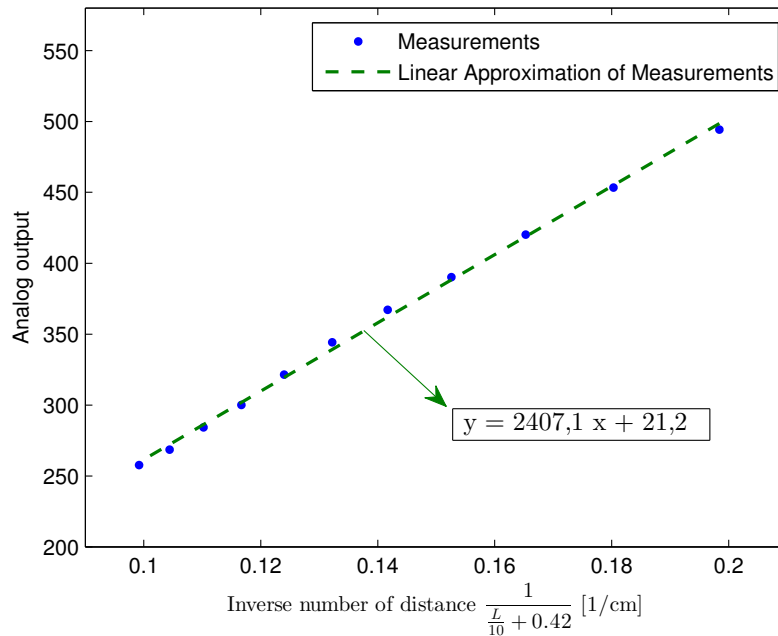


Figure 2.55: Relation giving by the sensor datasheet and its linear approximation

2. It is also possible to invert the transfer function of Figure 2.53 and approximate the measurements with a fourth order polynomial function as depicted in Figure 2.56.

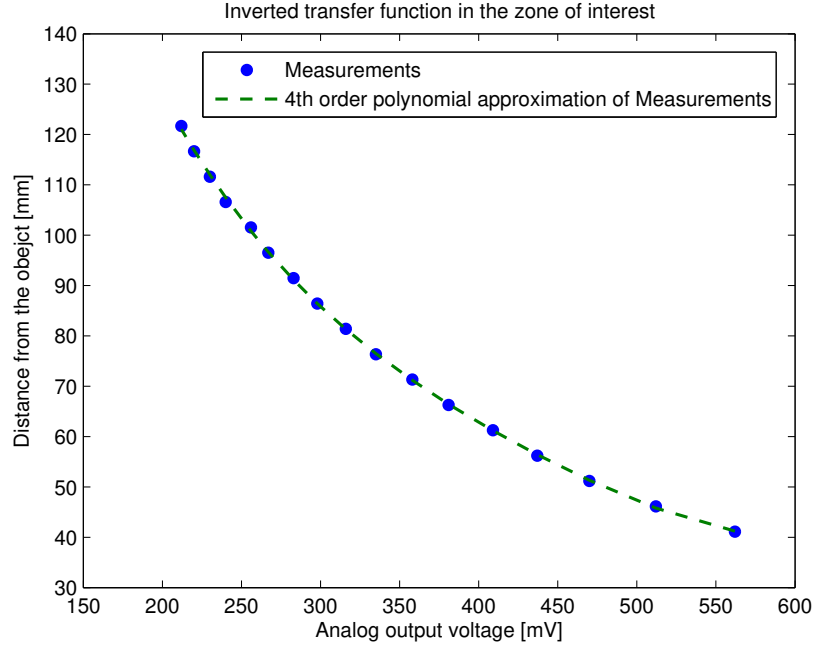


Figure 2.56: Inverted transfer function and its approximation with a fourth order polynomial

Figure 2.57 compares both methods on the same graph. The linear approximation of the ARDUINO output V in Figure 2.55 is transformed to isolate the distance L :

$$V = a \times \frac{1}{\frac{L}{10} + 0.42} + b \iff L = \left(\frac{1}{\frac{V-b}{a}} - 0.42 \right) \times 10$$

where $a = 2407.1$ and $b = 21.2$ are the parameters of the linear approximation.

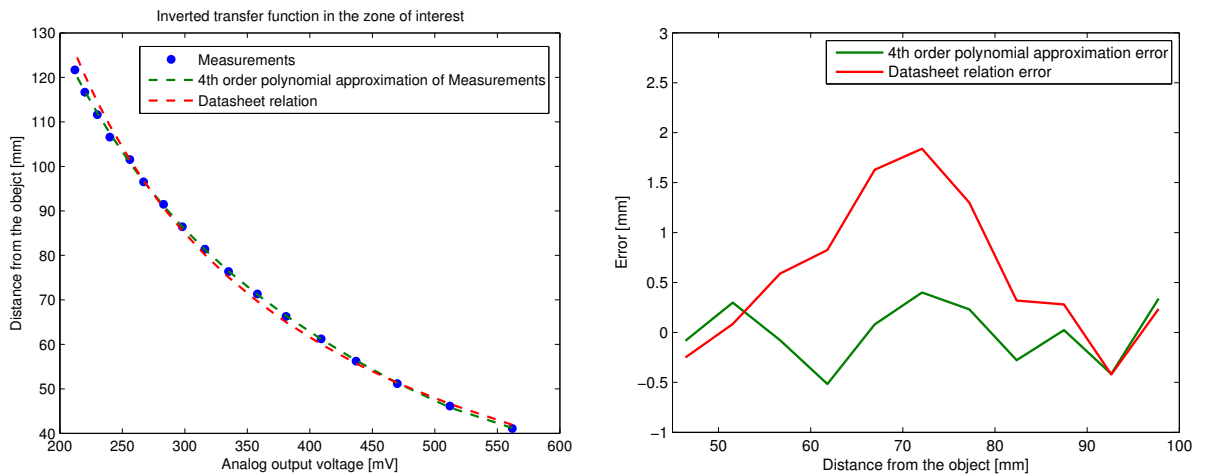


Figure 2.57: Comparison of the error given by both methods in the range [45 mm - 100 mm]

Since the fourth order polynomial introduces less error than the relation given by the datasheet, it will be used for the next steps of this thesis.

2.3.4 Computations for the robot repositioning

Now that the three sensors are assembled and that they give good measurements, it is time to use these measurements to approximate the targeted surface and to compute the position to place the laser head. The goal is to have the laser which is perpendicular to the approximated plane and which is at a distance of 100 mm to be in the center of its range.

Let us list the different quantities that are known. Firstly, the position of the origin of each sensor in the laser frame is known thanks to the mechanical interface fixing them together. These positions are noted P^i where i corresponds to the sensor number. Secondly, the emission line direction of the distance sensors are also available. These quantities are expressed thanks to the vectors $\mathbf{v}^i$ expressed in the laser head frame too. Finally, the distance measured by each sensor is noted d^i . The frame of the laser head and the different quantities are illustrated in Figure 2.58

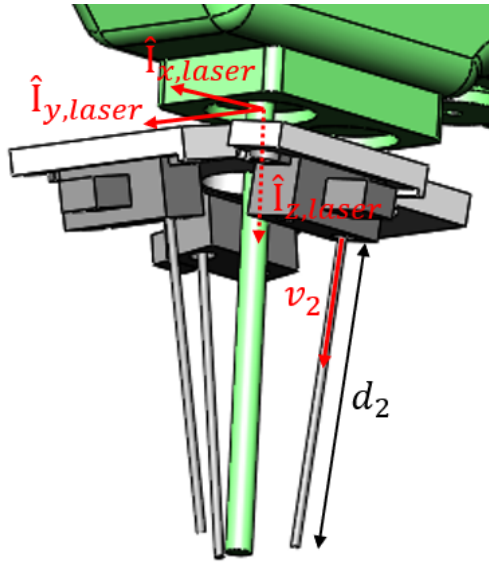


Figure 2.58: Geometric quantities of the solution using three distance sensors

Using this information, it is possible to compute the coordinates of the three points belonging to the targeted surface using the following equation :

$$O^i = P^i + d^i \cdot \mathbf{v}^i$$

where O^i corresponds to the coordinates of the three points belonging to the targeted surface.

Once these points are found, the same technique as the one concerning the SENSE is applied. The difference is that the laser frame is used instead of the robot frame. Nevertheless, this is not an issue because the robot gives the transformation matrices to retrieve the coordinates in the robot frame.

In practice, this is not even used since the repositioning of the robot can also be done in the frame of the tool, so the frame of the laser head.

2.4 Summary

This chapter explained how both solutions selected in the first chapter were implemented. For both solutions, a mechanical interface has been designed in order to fix precisely the system to the robot. This robot allowed us to perform several tests to study the behavior of the selected products. Finally, based on the measurement of both systems, a positioning instruction for the robot was computed.

Figures 2.59 and 2.60 remind these two solutions.

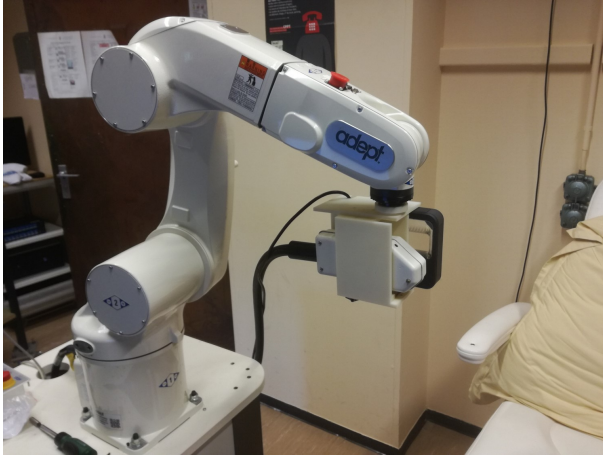


Figure 2.59: Solution using the SENSE 3D scanner

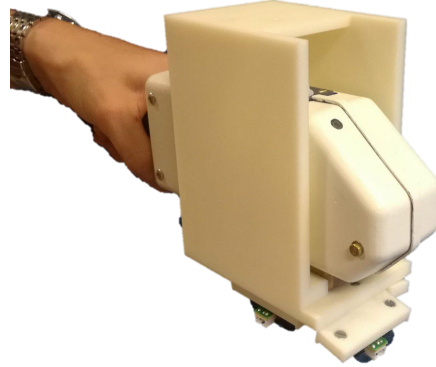


Figure 2.60: Solution using the three distance sensors

At this stage, each implementation could be used to send its computations to the robot to reposition the laser head. The next chapter is dedicated to the experimental comparison. Through several experiments, both devices are placed in several situations in order to find their differences and limitations.

At this step of the work, it is needed to highlight the advantages, disadvantages and limitations of both solutions in order to keep the best ones that will be embedded on a robot or another system. The following experimental comparison presents the procedure in order to differentiate both solutions. To reach this objective, several tests will be performed. For each test, the followed methodology, the material used, and the results obtained are successively presented. At the end of each experiment, the results are discussed describing the impact of the parameter on the performance of the device. Finally, both solutions are compared leading to the final candidate.

3.1 Tests performed

The solutions will be differentiated based on several criteria. For each of them, it is explained why studying the effect of this criterion and how it is simulated in practice through experiments. Finally, the results are analyzed and discussed to quantify the impact of each criterion.

3.1.1 General materials

Here is the list of general equipment used to obtain and process the data for all experiments.

Hardware

- 3 distance sensors : SHARP GP2Y0A41SK0F
- 3D scanner : SENSE 2
- Micro-controller : ARDUINO UNO
- Industrial robot Viper s650 (refer to Section 2.1)

Software

- ARDUINO : retrieve the data of the distance sensors and compute the new position of the laser head
- SENSE : build the 3D model and save the data in OBJ format
- MATLAB® : process the SENSE data, compute the normal and plot the results

3.1.2 Environmental parameters

The device should work in a classical hospital room. Some parameters could influence the behavior during the experiment performed by the neurologist.

a. Luminosity

The luminosity is the main criteria as regards to environmental parameters. The lighting conditions could be changed in several situations :

1. The laser head shades the target during the experiment by going over it ;
2. The sun illuminates the scene which can disturb the sensing device behavior ;
3. An indirect effect of the change in luminosity can also happen if the patient wears a jewel like a ring or a bracelet that reflects light.

Experiment 1: To see if the area shaded by the laser affects the results, three situations were analyzed as depicted in Figure 3.1. The first case is a classical lighting with neon lights like in most hospital buildings. The second one is performed using a spot with adjustable brightness preventing to have shadows on the scene. The last one is done when turning off the lights. The same experiments were performed for both the 3D scanner and distance sensor.



Figure 3.1: Experimental setup for testing the SENSE in different lighting conditions : classical lighting (neon lights), spot and no lighting

Results: the lighting conditions of the room does not have any relevant impact on both devices as shown in Figures 3.2 and 3.3.

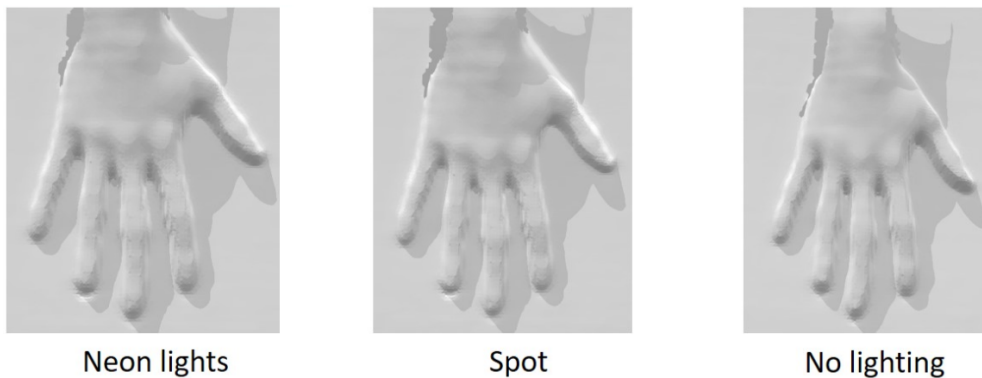


Figure 3.2: Results of the influence of lighting conditions for the SENSE : classical lighting (neon lights), spot and no lighting

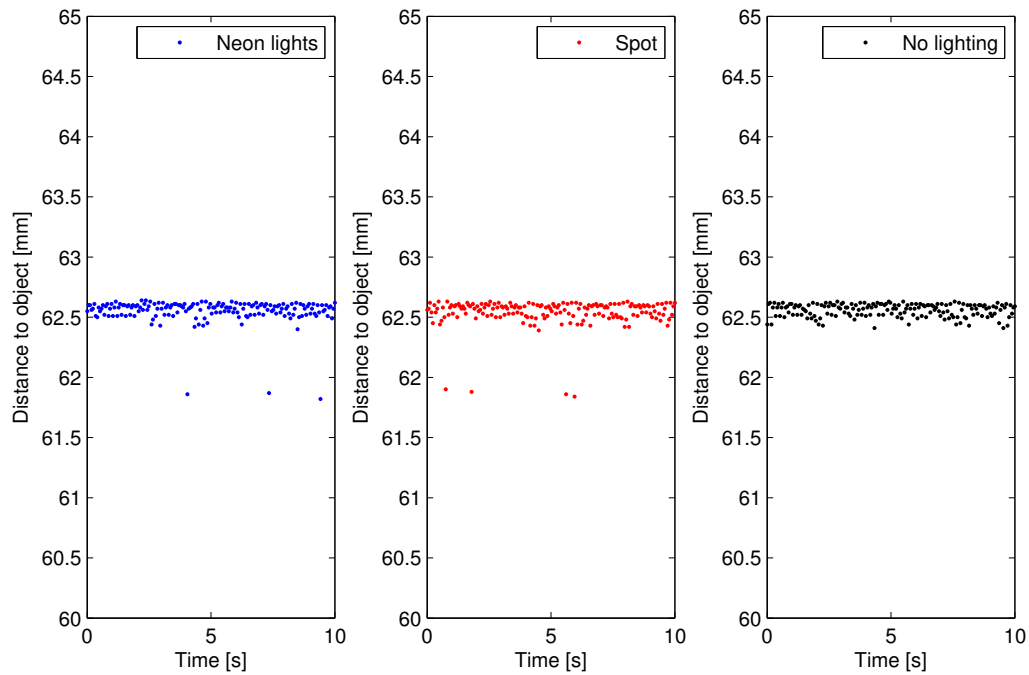


Figure 3.3: Results of the influence of lighting conditions for the SHARP : classical lighting (neon lights), spot and no lighting

Experiment 2: Influence of sunlight is tested in two ways. For the 3D scanner, the hand is positioned with a part shaded and a part in direct sunlight as in Figure 3.4. As regards the distance sensor, it is fixed on a wall while observing a white sheet of paper separated by 70 mm for 10 seconds as illustrated in Figure 3.5. The sheet is shaded thanks to a plate. Twice, the plate is removed so that the sheet is in the sunlight during about two seconds.



Figure 3.4: Experimental setup testing the sunlight influence on the SENSE

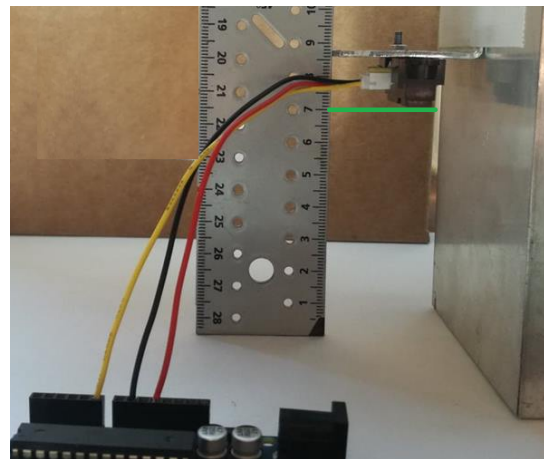


Figure 3.5: Experimental setup testing the sunlight influence on the SHARP

Results: As depicted in Figures 3.6 and 3.7, the sun has an important influence on both measuring systems. The 3D scanner is not able to see the area in the sunlight. Regarding the distance sensor, the measurement drops suddenly to a lower value.

It is therefore forbidden to place the patient in direct sunlight.



Figure 3.6: Influence of the sunlight on scan rendering of the SENSE

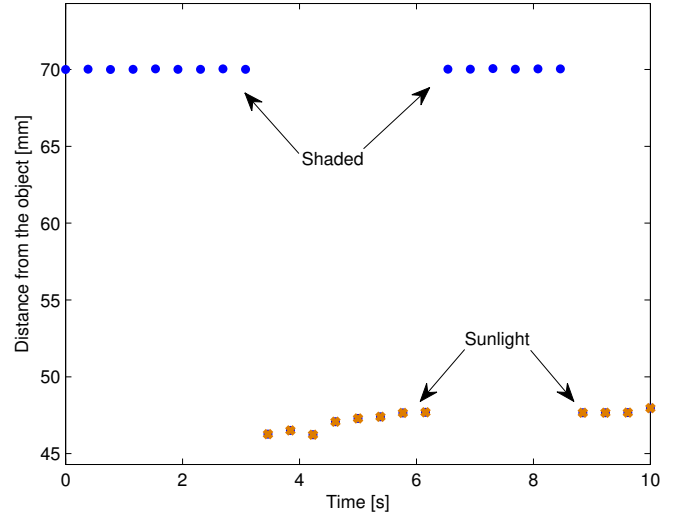


Figure 3.7: Influence of the sunlight on SHARP measurements

Experiment 3: the last experiment regarding the luminosity is only performed for the 3D scanner. Figure 3.8 shows a scan while wearing a metallic watch and a metallic ring.



Figure 3.8: Influence of reflecting objects like a metallic watch and a metallic ring

Results: Figure 3.8 shows that jewels have a poor scan quality. However, it does not affect the rendering in the stimulation zone. Moreover, the neurologist generally asks people to remove those jewels since it is potentially dangerous while using the stimulation laser.

b. Temperature

The SENSE datasheet mentions that the scanner must operate in a temperature ranging from 10° to 40°C [36]. The SHARP measurement is not influenced by the environmental temperature according to its datasheet [37]. Since the temperature in a hospital is controlled to be around 20°C, this criterion does not need to be tested.

3.1.3 Skin parameters

The skin could also differ from one patient to another. Everyone has a different vascularity, skin color and hairiness. The age of the patient is not a criterion itself since it is somewhat included in the vascularity.

a. Vascularity

As discussed in Section 2.2.2 the 3D scanner is not able to detect irregularities. However, it can ignore them so that the position of the laser head is not affected.

For the distance sensors, this is not the case. As explained, earlier, a sensor could point toward an irregularity. In this case, the measured distance would be smaller or larger, and the device would then consider that the targeted surface is tilted whereas it is flat.

Experiment: to simulate the effect of an irregularity, different pieces of known thicknesses are placed under a sensor as in Figure 3.9. The heights of the pieces tested are 1.5, 3 and 6 mm. The piece is placed below each sensor one after the other. For each case, distance measured by all sensors is used to compute the induced rotations along 'X' and 'Y' (refer to Figure 3.10 for the axes). The objective of this test is to determine the limit of acceptable skin irregularities. As a reminder, the tilting error must be less than 15° according to FR 2.1. of the specifications.

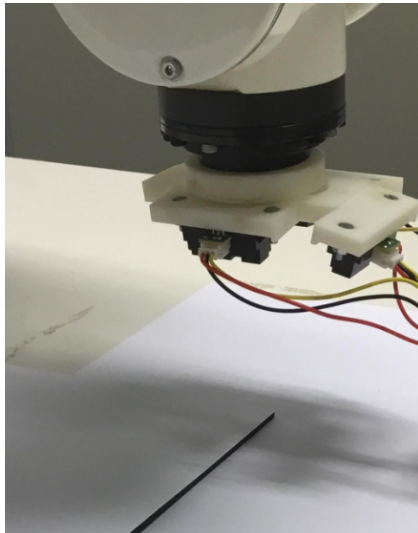


Figure 3.9: Experiment realized to simulate the effect of the vascularity. Here, a wooden plate of 3 mm is placed below the right rear sensor.

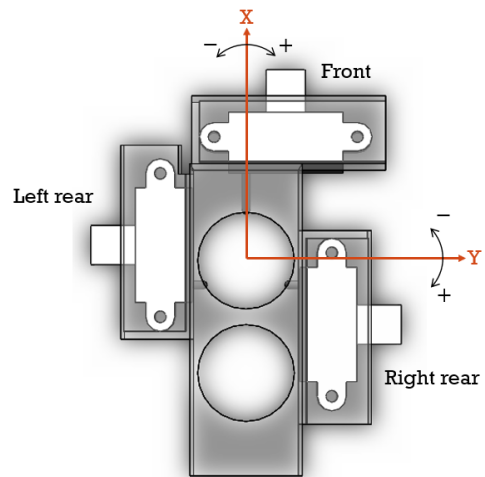


Figure 3.10: Upper view of the system with a labeling of the sensors and a representation of the axes

Results: When facing the flat table at 70mm, the system already computes that the laser head needs to be tilted of 1° along 'X' and 0.8° along 'Y'. The sensors tilting angle as well as the mechanical interface seem to introduce inaccuracy.

Figure 3.11 illustrates the error for different distances while again facing the flat table. This experiment is performed to see if it is possible to correct the previous error. An offset is observed on the 'Y' axis error probably due to a difference in measurements of the front and rear sensors. The objective is to decrease the error in the laser range (85–115 mm) equivalent to about 55–85 mm for the sensors. By applying a correction factor on sensors characteristics, the results in Figure 3.12 are obtained. The maximal error is 3.5° along X when the laser is at 120 mm and the maximal error is 1.1° along 'Y' when the laser is at 130 mm.

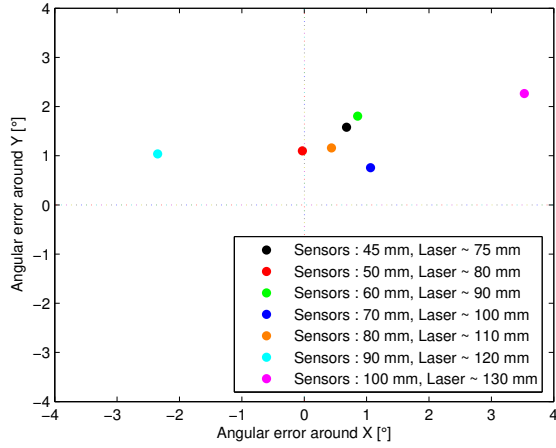


Figure 3.11: Induced rotations along X and Y axes facing the flat table for different distances

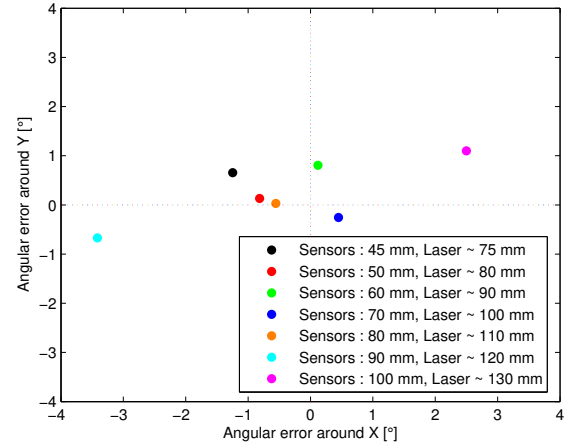


Figure 3.12: Induced rotations along X and Y axes facing the flat table for different distances *with correction*

Next, the black dot, the circles, crosses and squares represent respectively the tests performed for the flat surface, 1.5, 3 mm and 6 mm. For example, placing a 3 mm plate under the right rear sensor is inducing a rotation along -X and -Y. Indeed, as depicted in Figure 3.10, the right rear sensor is measuring a shorter distance than the others. The system therefore compensates with a rotation along -X and -Y. The angular error remains acceptable until 3 mm but exceeds a bit the limit of 15° for 6 mm.

However, it should not be an issue since the skin irregularities are rarely more than 3 mm thick.

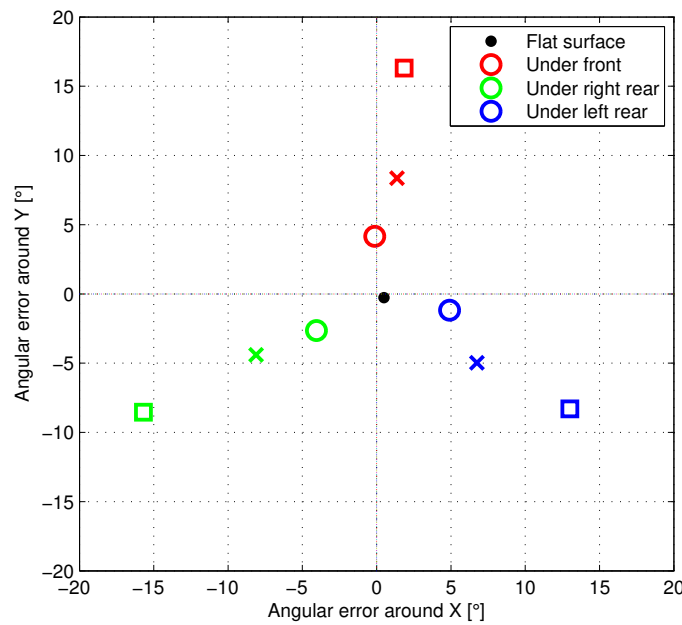


Figure 3.13: Induced rotations along X and Y axes due to irregularities for different thicknesses

b. Skin color

The effect of the skin color and of a tattoo is also evaluated. Indeed, tattoos are sometimes made of different colors than black or white which are all in the same color tone.

Experiment 1: To simulate the effect of a tattoo, different colored sheets of paper are successively placed below the sensors as shown in Figure 3.15. Then, the measurements of one of them were recorded. Regarding the 3D scanner, the sheets were fixed on a foot prosthesis like in Figure 3.14.



Figure 3.14: To simulate the tattoo, colored sheets of paper are fixed on a foot prosthesis

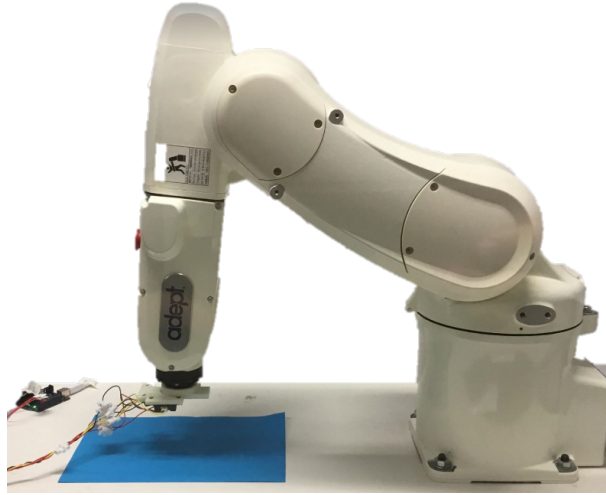


Figure 3.15: A sheet of paper is placed below the device of three distance sensors

Results: The boundary between the black and blue sheets is not correctly scanned as shown in Figure 3.16. The dark color seems to perturb the distance sensor since the measurements increase significantly as illustrated in Figure 3.17. However, since we were not able to find a tattooed person, these results may not reflect the reality since the skin does not have the same behavior as a sheet of paper.



Figure 3.16: Influence of the color on the SENSE

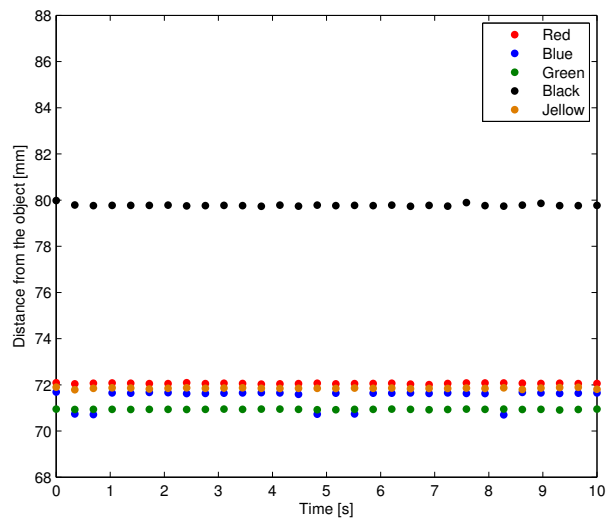


Figure 3.17: Influence of the color on SHARP measurements

Experiment 2: Previously, the hand of a white-skin person has been studied. Now, taking the other extreme, the hand of a black-skinned person is scanned.

Results: Figure 3.18 shows that there is not difference with the scan of a white-skinned hand.

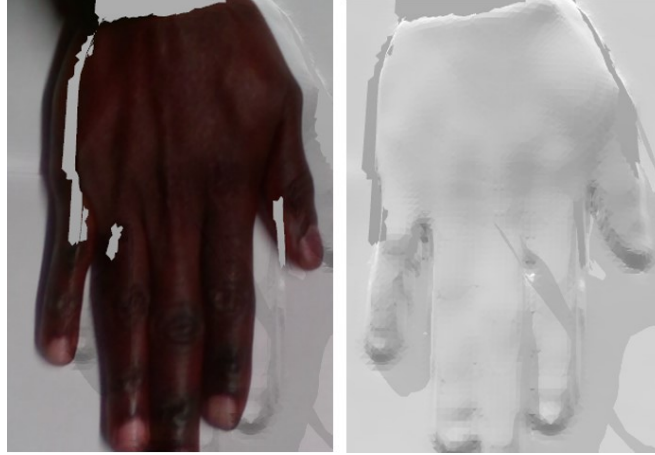


Figure 3.18: Scan of a black-skinned person

c. Hairiness

If too hairy, the patient is shaved because hairs prevent to stimulate the skin correctly. Anyway, the hairiness does not have an influence on the scan rendering as illustrated in Figure 3.19. The arm has the same rendering as the hand. However, verifying with the sensor is more complex.



Figure 3.19: Influence of the hairiness

3.1.4 Precision and accuracy

To test the precision and accuracy of both devices, the robot positions the devices in different situations

Distance sensors

The robot is tilted at an angle along X and Y from -40° to 40° with a step of 10° . Figure 3.20 shows the case where the robot end-effector is tilted of 40° along X and of -30° along Y. The distance sensors are pointing to the table and take measurements for 10 seconds. The correction to apply such that the robot returns to the vertical orientation compared to the table is computed. For each case, the output is thus an angle along X and Y.

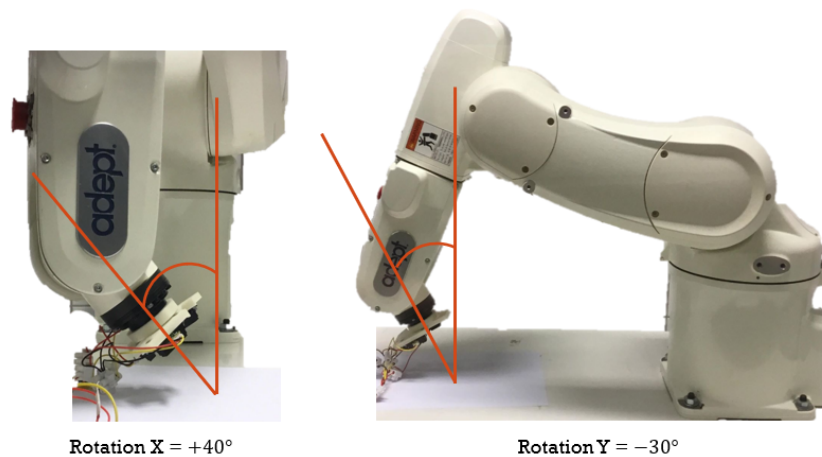


Figure 3.20: Examples of tilting using the Viper s650

Figure 3.21 gathers the results for all cases. Each color is linked to a specific orientation ($\pm X/Y$): red for 10° , green for 20° , orange for 30° and black for 40° . The stars represent the orientation of the robot end-effector which is supposed to be correct given the robot precision. For instance, the situations of Figure 3.20 are the black star on the right ($+40^\circ$) and the down orange star (-30°). Next, the dots are the results of the sensors computations. It tells the robot of how many degrees it has to rotate along 'X' and 'Y' to come back to a position perpendicular to the table ($X = 0^\circ$ and $Y = 0^\circ$). However, for a reason of clarity, the sign of the rotations are reversed to make the graph easy to understand. For example, if the robot rotates of $+10^\circ$ along 'X', the sensors tell the robot to rotate of -9.5° along X and 0.9° along Y. But here, the sign in the MATLAB[®] program is changed to plot a positive angle along 'X' since the idea is to highlight the sensors precision and accuracy.

For every case, 30 points around the star are plotted. The closer the dots are from the stars, the better is the result. In general, the computations are precise but the accuracy varies according to the situation.

When the robot is tilted of $+40^\circ$ along 'X', the X error occurs and is equal to 3.3° . The Y error occurs when the robot is tilted of -40° and is equal to 3.3° .

The maximal error when the robot is tilted along 'Y' occurs for -40° with an error of 8.9° along 'X' and 4.5° along 'Y'.

It can be observed that the X error increases as the robot tilting angle along Y increases. This could come from the two rear sensors that are not exactly measuring the same distance. They are also tilted from an opposite angle. As the robot is tilted along Y, this error may be amplified as the distance measured by both sensors increases.

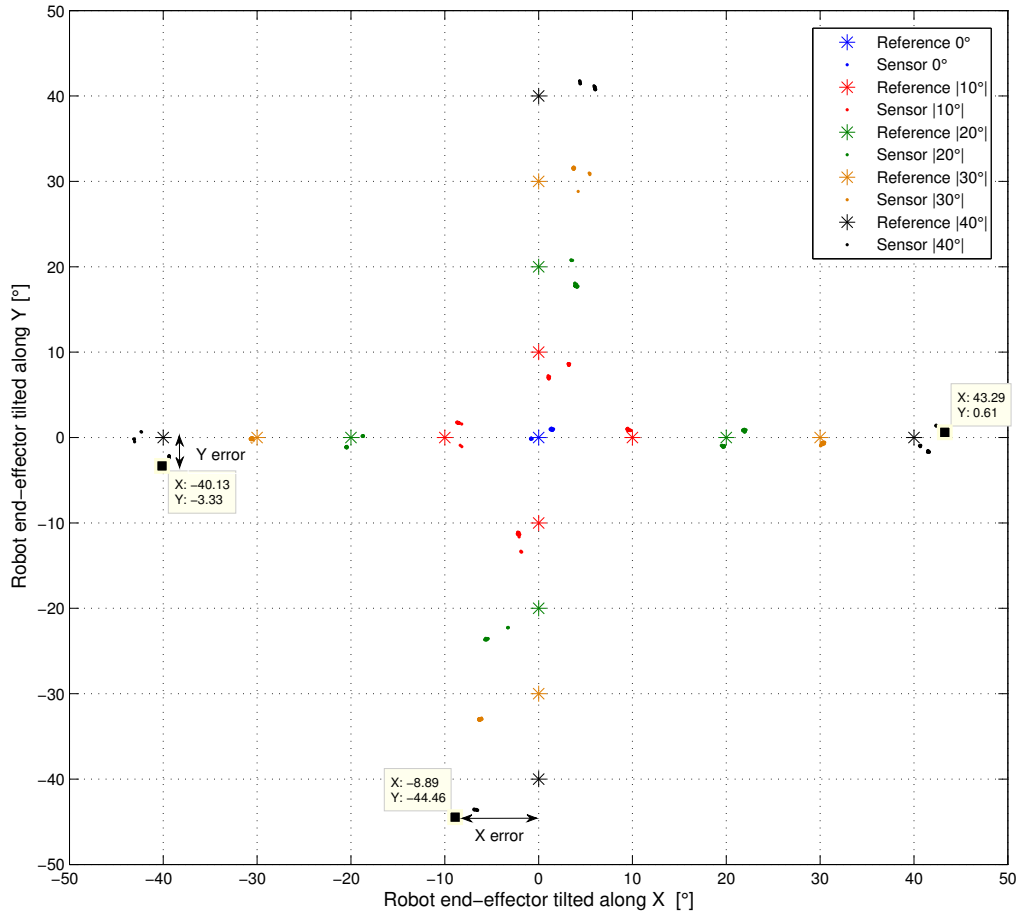


Figure 3.21: Tilting of the robot

Sense

For the 3D scanner, the previous experiment with the sensors cannot be applied. Indeed, as explained earlier, the robot moves the scanner to perform the scan. But if there is nothing to scan on the table, the scanner loses the tracking. Therefore, a tilted plate on the table is placed. The situation is illustrated in Figure 3.22 with three different angles tested. Then, the angles will be extracted from the scan file.

To create the slopes, metallic pieces and a plate with known dimensions are used. The distance between the two contact points of the plate was 280 mm and the different height of the modules were respectively 40.4 mm, 79.5 mm and 158.8 mm. Knowing that, the angle of each slope is respectively 8.3°, 16.5° and 34.6°.



Figure 3.22: Experiment where the SENSE scans a plate with three different angles : 8.3° , 16.5° and 34.6°

Once the scans are recorded, it is possible to determine the slope detected by the 3D scanner. The local normal at different locations on the scan is computed to detect variations. Figures 3.23 and 3.24 show the normals computed along the 'Y' direction. The same procedure is performed along the 'X' direction.

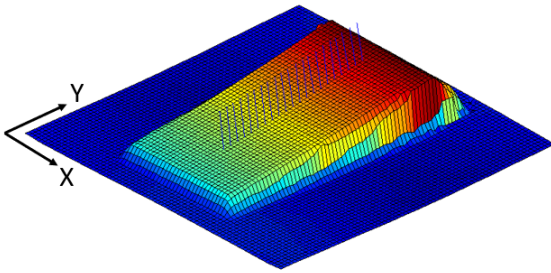


Figure 3.23: Normals computed along the 'Y' direction

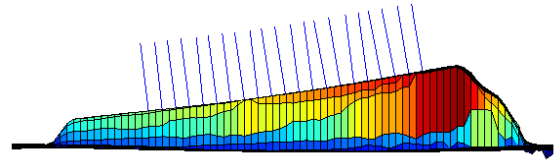


Figure 3.24: Lateral view of the normals computed along the 'Y' direction

Figures 3.25 and 3.26 show respectively the measured angles for the three tilting angles of the plate. For each set of measurements, an approximation of the first order is realized to identify if there is a constant tendency that could be corrected.

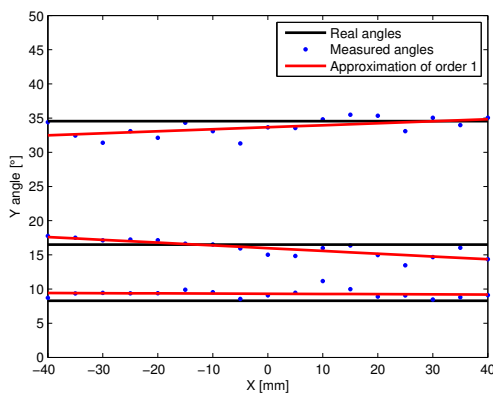


Figure 3.25: Angles measured along the 'X' direction at $Y = 0$

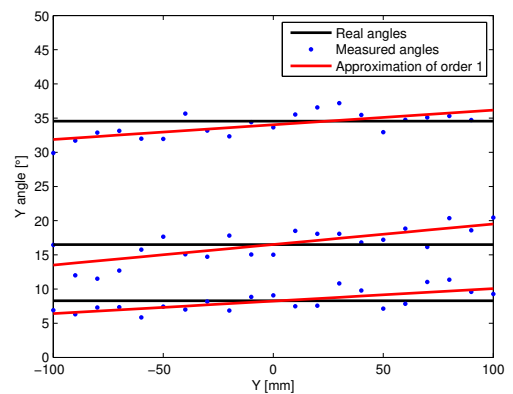


Figure 3.26: Angles measured along the 'Y' direction at $X = 0$

In Figure 3.25, there is no constant tendency. For 8.3° , the approximation is horizontal, for 16.5° it decreases and for 34.6° it increases. But in Figure 3.26, the approximation always increases for each tilting angle. This means that the scanner sees a flat surface as a curved surface as it can be slightly seen in Figure 3.24. But since the approximations have a similar slope, it means that the curvature is always the same. Therefore, it is possible to rectify it by integrating the slope on the model. After the correction, the results in Figure 3.28 are obtained.

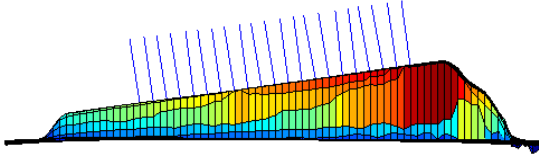


Figure 3.27: Lateral view of the normals computed along the 'Y' direction with the corrected curvature

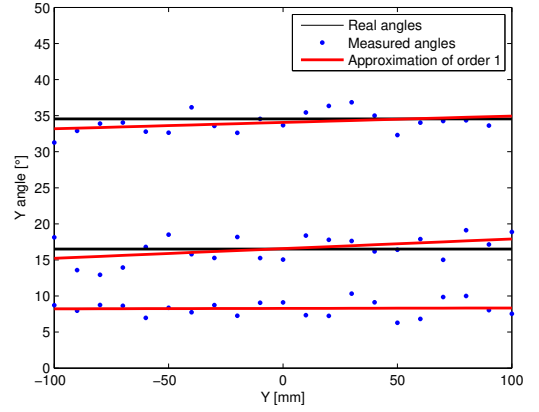


Figure 3.28: Angles measured along the 'Y' direction at $X = 0$ with the corrected curvature

Figure 3.28 shows that the surface of the plate tilted of 8.3° is completely flat and that the curvature for the two others is decreased. Furthermore, Figure 3.27 illustrates the plane of the table that is now slightly curved down. However, since the profile of a hand or a foot is also tilted like the plate, the hand or the foot shape has been preferred instead of the table shape.

In the end, the SENSE scanner has a good angular accuracy because in the worst cases, the approximation has an error of maximum 3° . Moreover, the accuracy is even better in the center where will be placed hand or foot. The precision is also good because the maximum error for the three different cases is of about 4° .

There are two ways to improve the scan precision. The idea is to increase the number of points taken to compute the means assigned to the 'Z' component of the mesh. The first way is to increase the radius of the means during the computation of the mesh. As explained in the implementation, this will smooth the surface and decrease the irregularities. Nevertheless, the risk is to change the shape of the scanned object. The second way is to increase the resolution. However, dealing with more points will increase the computation time.

Concerning the precision in distance, a scan of a metallic block with precisely known dimensions is realized (Figure 3.29). The block height is 40.4 mm. As Figure 3.30 shows, the depth precision and accuracy of the scanner are less than 1 mm at 50 cm of distance.



Figure 3.29: Scan of a reference object with known dimensions

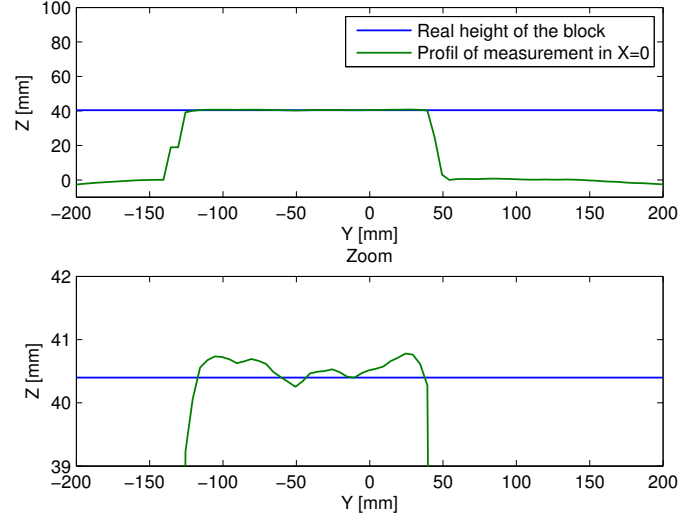


Figure 3.30: Profile of measurement along the 'Y' axis in X=0

3.1.5 Processing time

The processing time is composed of the time required to perform the measurement by the system and of the time to calculate the repositioning of the robot end-effector.

For the 3D scanner, the measurement consists of performing the scan. This operation is done before the experiment and if the patient moves, the user will have to stop the experiment and repeat it.

The total time needed to perform the scan is the sum of the time for the robot to make the move (20 seconds), the time for the software to assemble the measurements and to create a 3D model (10 seconds with a low resolution), the time for the user to inspect the scan quality and save it in a specific folder (approximately 30 seconds), the time for the software controlling the robot to extract the data, to put them in the frame of the robot and reorder them (15 seconds using MATLAB®). The total time is approximately 75 seconds.

Once this is done, the experiment can begin and the software controlling the robot just has to compute the correct position of the laser head based on its current position and the created mesh. This action takes only a few milliseconds and is not a limitation for the robot to replace itself on time. The time between two stimulations is maximum 10 seconds according to FR 2.5 of the specifications.

Regarding the distance sensors, the measurement are done during the experiment. Therefore, even if the patient moves, the device will take it into account without losing time.

To make the measurements and compute the correct position of the laser head, it takes approximately 0.2 second. The majority of the time lost corresponds to the delays of 20 ms to switch the sensors on and off. This leads to a total delay of 120 ms.

However, 0.2 seconds is fast enough to reposition the robot within the allotted 10 seconds.

Results: before the experiment, the 3D scanner needs to make a 3D model of the target which takes approximately 75 seconds. Moreover, this operation has to be repeated if the patient accidentally moves. Since this is not the case for the distance sensors device, this solution looks better.

3.1.6 Stimulation area

Are the devices able to target the whole hand and foot dorsum as in Figure 4 ?

As mentioned in Section 2.3, the distance sensors device has a limited sensing zone because of the structure maintaining the sensors together. The laser head is constantly replaced at a distance of 100 mm compared to the skin. In this position, the points belonging to the skin surface measured by the sensors are on a circle of 25 mm diameter. The distance from the hand or foot edges is therefore 12.5 mm.

However, the 3D scanner is able to see the whole hand given previous experiments. The worth scenario is when two feet are stimulated.

Results: in the case of two feet, a small area is not detected as illustrated in Figure 3.31. The 3D scanner offers a larger stimulation area.

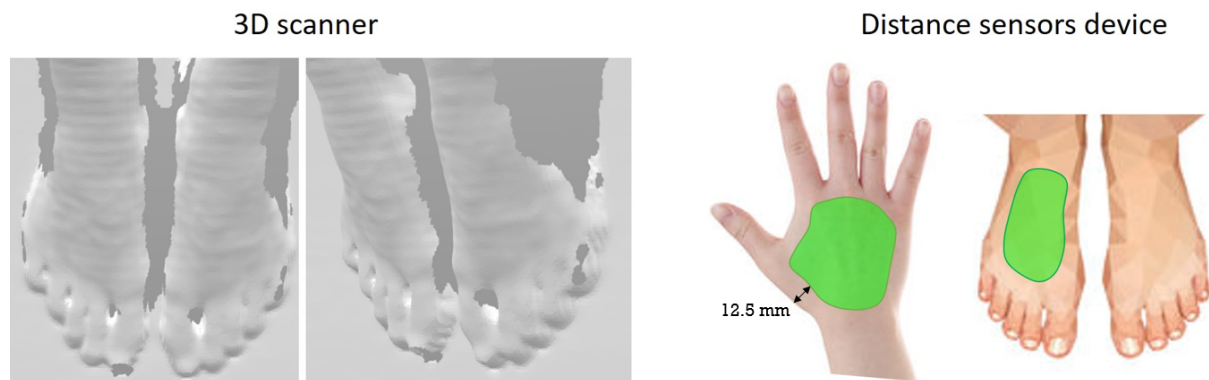


Figure 3.31: Sensing areas of both devices

3.1.7 Sustainability

Since the device will be used during at least 5 years with possible maintenance operations (CR 5.2 of the specifications), the sustainability is a key factor too. The sensors solution is likely to be more sustainable than the one using a 3D scanner. Indeed, once the SENSE is no longer manufactured, the solution is no longer valid.

However, as long as the SENSE is manufactured, it is only needed to interchange the old one with the new one. The interface piece, the software and everything else remain the same. Whereas for the distance sensors, if one of them is not working correctly, it is needed to calibrate it again. Indeed, every manufactured sensor has a different transfer function.

3.2 Discussions and final choice

At the end of this experimental protocol, let us summarize in Table 3.1 the criteria and their impact on both solutions.

- Luminosity : neither device seems to be influenced by artificial light, but both of them are strongly influenced by sunlight. Since hospital rooms are generally provided with curtains that can be closed, we may admit that this criterion is not relevant in making our choice.
- Color : a tattoo was simulated thanks to colored sheets of paper. For both devices, a black colored paper has an impact. However, scanning a black-skinned person does not influence the scan performances. Therefore, these results may not reflect reality since the skin does not have the same behavior as a sheet of paper. The probability of having a patient with a tattoo on his hand and/or foot dorsum is unlikely to happen. Moreover, the laser itself does not work on a black skin.

- Precision and accuracy : both systems were tested on a flat surface to quantify the error they make.

The system using distance sensors is more accurate to measure the tilting angle of surfaces rotated around the 'X' axis than around the 'Y' axis. Indeed, even for a surface tilted of 40° , the system presents an error of maximum 3° . However, the accuracy evolves with the rotation angle around the 'Y' axis. When the surface is tilted of 40° , it makes an error of 9° . However, this is still under the 15° required. The precision does not exceed 2° .

For the 3D scanner, the depth accuracy is better than 1mm. Concerning the measurement of the angle, the scan is a bit curved which leads to a bad accuracy at the edges of the scan. However, the error in accuracy does not exceed 3° and the limb to scan is placed in the center of the scan area. The error in precision can go up to 3° .

This test was for flat surfaces. However, hand and foot are curved and they may have surface irregularities. It influences the angle measurement with the system using sensors but not with the scanner because the low resolution of the latter smooths the scanned surface. In conclusion, the 3D scanner gives a precise measurement with an error always below 15° . For the distance sensors, it is preferable to target a surface which is not too curved and containing only small irregularities to ensure an error below 15° .

- Processing time : the main downside of the 3D scanner is its inability to take into account movements of the patient. If the patient moves during the experiment, the 3D model of the target has to be reconstructed, which takes approximately 75 seconds. Distance sensors are not affected by movements of the patient and are able to provide a new command to the robot every 0.2 seconds.
- Stimulation area : because of its structure, the distance sensor device is not capable of measuring complete hand and foot areas. The laser is allowed to stimulate the skin until it is at a distance of maximum 12.5 mm from the edge. With the specific movement of the 3D scanner, a complete view of the hand is delivered. When scanning two feet side by side, a small area is not detected but this remains acceptable.
- Sustainability : once the SENSE is not on the market anymore, a complete new solution will have to be designed based on another 3D scanner. The principle of the solution using three distance sensors is more sustainable because one may use any distance sensor having similar or better precision and accuracy, without having to redesign the complete system.

Criteria	Weight	3D scanner	Distance sensors
Luminosity	1		
Color	1		
Precision and Accuracy	2		
Processing time	2		
Stimulation Area	1		
Sustainability	1		

Table 3.1: Criteria summary

After several discussions with André Mouraux, we all concluded that it is difficult to differentiate the two solutions. The best one could be found with repeated use and time. Both solutions can be applied in different kinds of experiments :

- ① The 3D scanner would be interesting for research purposes where the patient is more compliant and is less likely to move. For example, some experiments are performed using long stimulation. In this particular case, the laser head has to be maintained during approximately a minute above the patient skin in the laser distance range. Otherwise, the laser disarms itself. In addition, the laser also has to be moved above the skin to avoid burning it by remaining in the same location. These experiments need a higher precision to stimulate specific skin areas.
- ② The distance sensor device is interesting since it allows a manual version. By combining it with a hand-held laser, the user has now a real-time information concerning both the distance to the skin and the relative orientation between the laser beam and the normal to the skin. However, since this system is less robust than the previous one, it is preferably dedicated to experiments where the neurologist only needs to briefly stimulate the skin in a random area.

For a future work, the first solution is constrained by the use of additional elements. Indeed, the first image taken by the laser is a key factor for positioning the target compared to the laser head. A robot could hold the laser and the 3D scanner as done in this master thesis. It has the advantage of being highly robust and of allowing to position the whole system in any configuration in space above the target. The neurologist could also control the robot using a joystick and a graphical interface.

Regarding the second solution, the idea is to keep a manual experiment by adding the distance sensor system directly on the laser head. It is made possible since the whole system is light and compact. A graphical interface could also be designed to let the neurologist know how far the laser is from the skin, how it is situated compared to it and what are the corrections to apply.

Let us summarize the work done during this year, the perspectives as regards a future work, the possible improvements that could be applied to the proposed solutions and finally the alternatives to solve the problems.

Summary of the work

The objective of this master thesis was to design, build and test a system capable of positioning correctly a laser head compared to a human hand or foot. The proposed solution is composed of a robot holding and positioning the laser head correctly thanks to a sensing device. By looking at existing technologies of sensing devices, two solutions appeared to be feasible. Both were implemented in order to compare them using an experimental protocol.

This report was divided in three chapters to describe each main objective of the work.

Chapter 1 was related to the design of the sensing device. A state of the art study was performed on two wide technologies being 3D scanners and distance sensors. On the one hand, 3D scanners are able to provide a global representation of an object by recording the coordinates of thousands of points belonging to the surface of said object. On the other hand, a distance sensor is able to measure the coordinates of one such point. However by performing continuous measurements around the targeted surface, it is possible to obtain an approximation of it in real time. Two commercial products were chosen : the SENSE[®] 3D scanner using structured light technology and the GP2Y0A41SK0F SHARP distance sensor using laser triangulation. Both solutions seemed promising but it was not possible at this stage to differentiate them on paper since the two technologies are fundamentally different.

In Chapter 2, the two solutions were implemented on an industrial robot available at the UCL. It was briefly presented. The different steps of implementation of both solutions were described.

Concerning the 3D scanner, the first objective was to create an optimal situation giving the best scan of a human hand. After testing a lot of parameters, the SENSE seems to be unable to differentiate irregularities on the hand.

For the distance sensors, the key objective was to guarantee a reliable measurement. Signal noise was greatly decreased, and the sensor was tested onto tilted surfaces. It was shown that the measurement could vary by 1 mm. A mechanical interface was designed to accurately fix the three sensors together on the laser head.

Chapter 3 presented the experimental comparison of both solutions. The goal was to differentiate these by highlighting respective advantages, disadvantages and limitations. The tests were related to environmental parameters such as lighting conditions and skin parameters such as vascularity and color. The other tests quantified precision, accuracy, processing time and stimulation area that each device is able to reach. The sustainability was also discussed. All these criteria were summarized in a table showing no clear evidence of a winner. Both had their own pros and cons, yet meeting the specifications listed at the beginning of this work.

Prof. André Mouraux's opinion is that each solution could be useful for different applications. The 3D scanner being more accurate with a maximal error in angle of 6° , it would rather be used for experiments that need to stimulate one particular point on the skin. This type of experiment is performed in a lab with people that are used to be stimulated by laser. These people are therefore less likely to move during the experiment and the scan will not have to be realized again.

The device composed of three distance sensors is less accurate. The error can be higher than the maximum error of 15° in exceptional situation. Nevertheless, it provides a new position every 0.2 seconds. It can also be used without robot. The device could be fixed directly on the laser head and provide real time information on the distance as well as the angle for a manual use. This could be useful for experiments that are performed at the patient's home where it is impossible to bring a robot.

Since the implementation of the complete solution using a robot is more time consuming, the client wanted us to focus on the solution using distance sensors.

Future prospects

The goal of this section is to give guidelines for further improvements of the technologies suggested in this work.

3D scanner (Sense[®])

Actions to finalize the current implementation The final robot is not yet defined. However a robot similar to the one used for this work is available at the IoNS. If we can use a CIDE key, the transfer of the work can be easily performed.

It would be more convenient for the customer to XY control the robot using a PC keyboard or a joystick.

Ideally, the scanner and the robot should be controlled by the same computer to ease the data transfer.

We have to take care that the movements of the robot is never a source of injuries to the patient. Once the final configuration is found, a certification could be needed.

Ways of improvement The system could be upgraded to make it capable to detect a movement of the patient and to determine if a new scan is needed. To improve a convenience of use, a graphic interface could be implemented. A 3D scanner with better performances could be used to improve the detection of skin irregularities.

If we find a way to prevent the patient from moving during testing, the test duration might be significantly reduced. A mold, shape memory foam or holding deformable materials could help. However, immobilizing the patient's hand or foot might not be a neutral solution because the cerebral response would probably be affected.

Distance sensors

Actions to finalize the current implementation If we consider the use of a robot to adapt the laser head position using real time data coming from distance sensors, a communication channel should be established between the ARDUINO board and the robot controller.

As an alternative, we could forget the use of the robot. In this case, the mechanical interface should be adapted. The system robustness should be improved because it would be used by people instead of a robot. Finally, a graphical interface could be implemented to give a feedback on distance and angle to the practitioner. A first prototype was already developed and shown in Figure 4.1. The correct distance and angle range are represented in green.

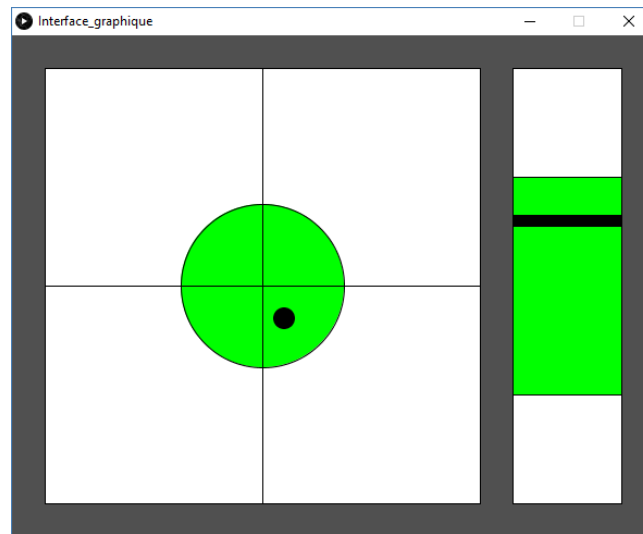


Figure 4.1: *Processing* graphical interface example

Ways of improvement Investments in sensors with higher performances (higher accuracy and output independent of angle) could be envisaged. We should find ways to improve flatness of hand and foot surface. Higher flatness meaning better accuracy on the angle evaluation.

Alternative designs

The solutions described in the works were the ones considered from the beginning. In the meantime, we believe there are other possible solutions. Furthermore, we have a better understanding of the requirements of the application.

If we do not consider the use of a robot, we must find a way to support the laser head. One way is to use a conical spring applying a constant force equal to the weight of the laser head. Another way could be the use of a structure that has a certain level of friction between joints. This enables to control the position of the laser head and maintain it when it is released. Another possibility is to use free joints equipped with electromechanical brakes.

Encoders could be arranged at each joint to retrieve the laser head position.

There may be an other solutions for the sensing device using laser triangulation technology. Instead of capturing the whole surface, the robot could be equipped with two crossed lines projector and one or two cameras to retrieve the local surface profile. This solution would give a better approximation of the skin surface than the solution using distance sensors and it would provide real time measurements.

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APPENDIX A

LIST OF SPECIFICATIONS

de Groote Maxant Thomas Alexandre		List of specifications Client: André Mouraux	Date : 03/11/17 Version : 5
Context: Positioning robot of a skin stimulation laser for the study of pain responses. The head of such a laser is by now manipulated by the neurologist, causing some precision errors. The robot and a measuring system must help increasing the precision of the laser by holding it and giving it the wanted position and orientation.			
Date	Origin	Main Functions	
27/09	Client	F1: Hold the laser head which can be removable from the robot	
27/09	Client	F2: Help the neurologist to position the laser head in space	
		Functional Requirement (FR) criteria and levels FR 1.1: Total weight of the optical fibre and the laser head: 540 g FR 1.2: Dimensions of the laser head (confidential) FR 1.3: Fixed thanks to a threading	
03/11	Client	FR 2.1: Orient autonomously the laser head normal to the surface of the skin with a maximal error of 15° (2 degrees of freedom)	
27/09	Client	FR 2.2: Position autonomously the laser at a distance from the skin between 85 and 115 mm (1 degree of freedom)	
27/09	Client	FR 2.3: The laser head position can be controlled manually along the "xy" plane of the Cartesian frame of reference	
11/10	Client	FR 2.4: The stimulated parts are the hand dorsum (50%) and foot dorsum (50%). Both hands or both feet can be stimulated during the same experiment. Refer to Annex I for the stimulation areas.	
18/10	Client	FR 2.5: Time between 2 stimuli: less than 10 seconds.	
03/11	Client		

		Main constraints
27/09	Client	C1: No contact with the patient skin
11/10	Client	C2: Safety
27/09	Client	C3: Transparent regarding the laser device
03/11	Client	C4: Location
11/10	Client	C5: Time of use
27/09	Client	C6: Limited optical fibre torsion
11/10	Client	C7: Ergonomics
27/09	Client	C8: Cost
		Constraint Requirement (CR) criteria and levels
11/10	Client	CR 2.1: Emergency stop button
11/10	Client	CR 2.2: Respect of European safety norms
11/10	Client	CR 2.3: Compliance with the Royal Decree of 12 August 1993 concerning the use of work equipment
03/11	Client	CR 4.1: Space available in the room for the robot, the laser stimulator, the patient, the operator and the EEG acquisition system: 4x4 m ²
27/09	Client	CR 4.2: Temperature range from 10° to 40°C
27/09	Client	CR 4.3: Electrical supply: 230V - 50Hz three-phase
03/11	Client	CR 5.1: Operational during at least 1h (time of a complete experiment) without interruption. 4-5 times/week
03/11	Client	CR 5.2: Lifespan: at least 5 years (200 hours/year) with possible maintenance operations
11/10	Client	CR 6.1: Maximal torsion of +/-180°
03/11	Client	CR 6.2: Minimum curvature radius of 25 cm
11/10	Client	CR 7.1: A person pilots the laser (a neurologist or a qualified person)

Appendix I: Stimulation areas for the experiments| - hand and foot dorsum



APPENDIX B

VL6180X RANGE PERFORMANCE

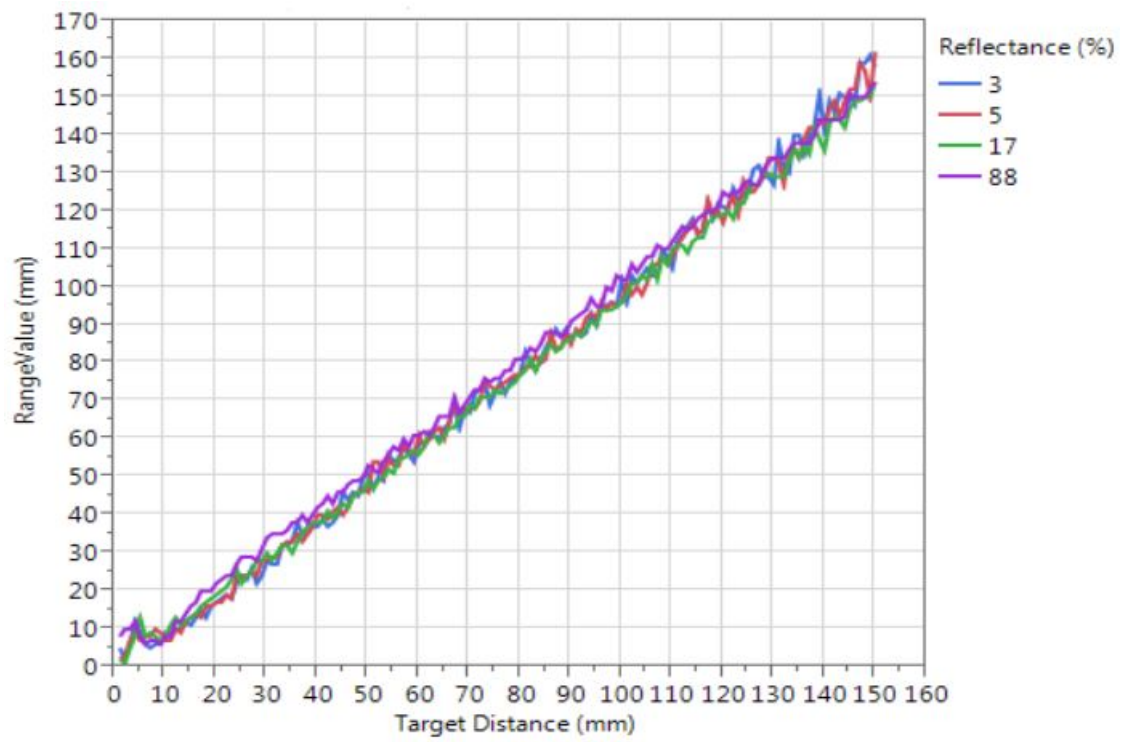


Figure B.1: Typical ranging performance of the VL6180X [39]

APPENDIX C

SHARP GP2Y0A41SK0F TRANSFER FUNCTION

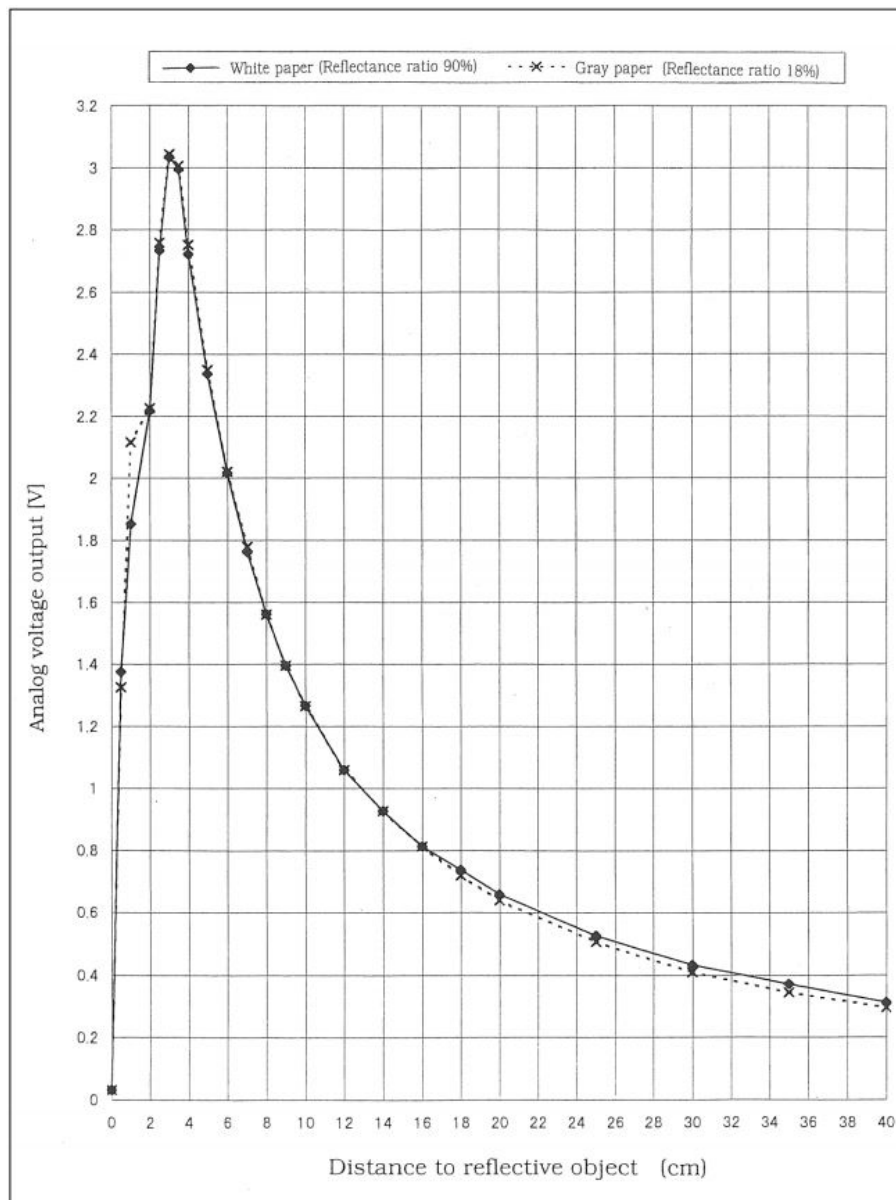


Figure C.1: Example of output distance characteristics of the SHARP GP2Y0A41SK0F [37]

APPENDIX D

INDUSTRIAL ROBOT : VIPER S650

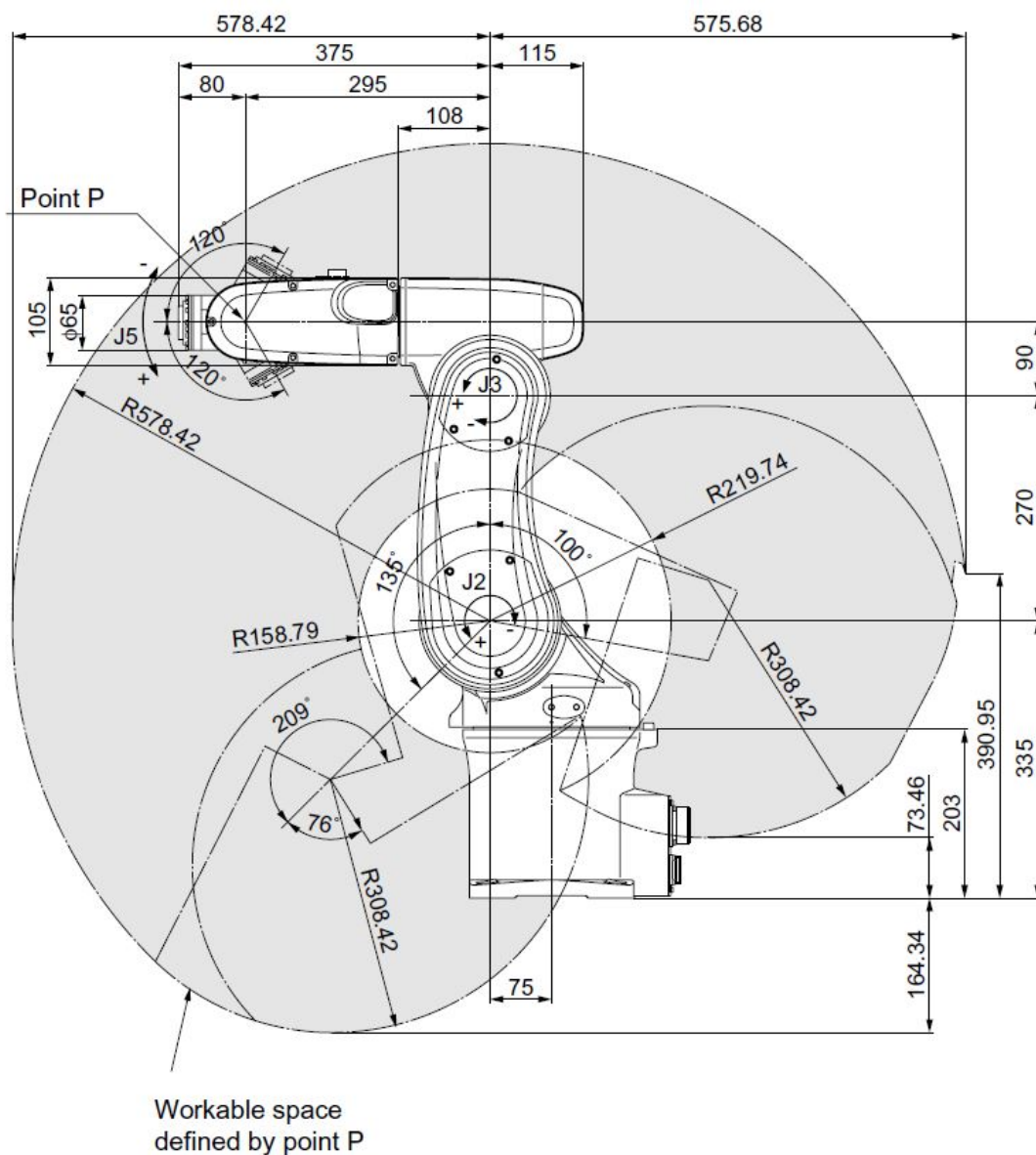


Figure D.1: Adept Viper s650 Side Dimensions and Work Envelope [40]

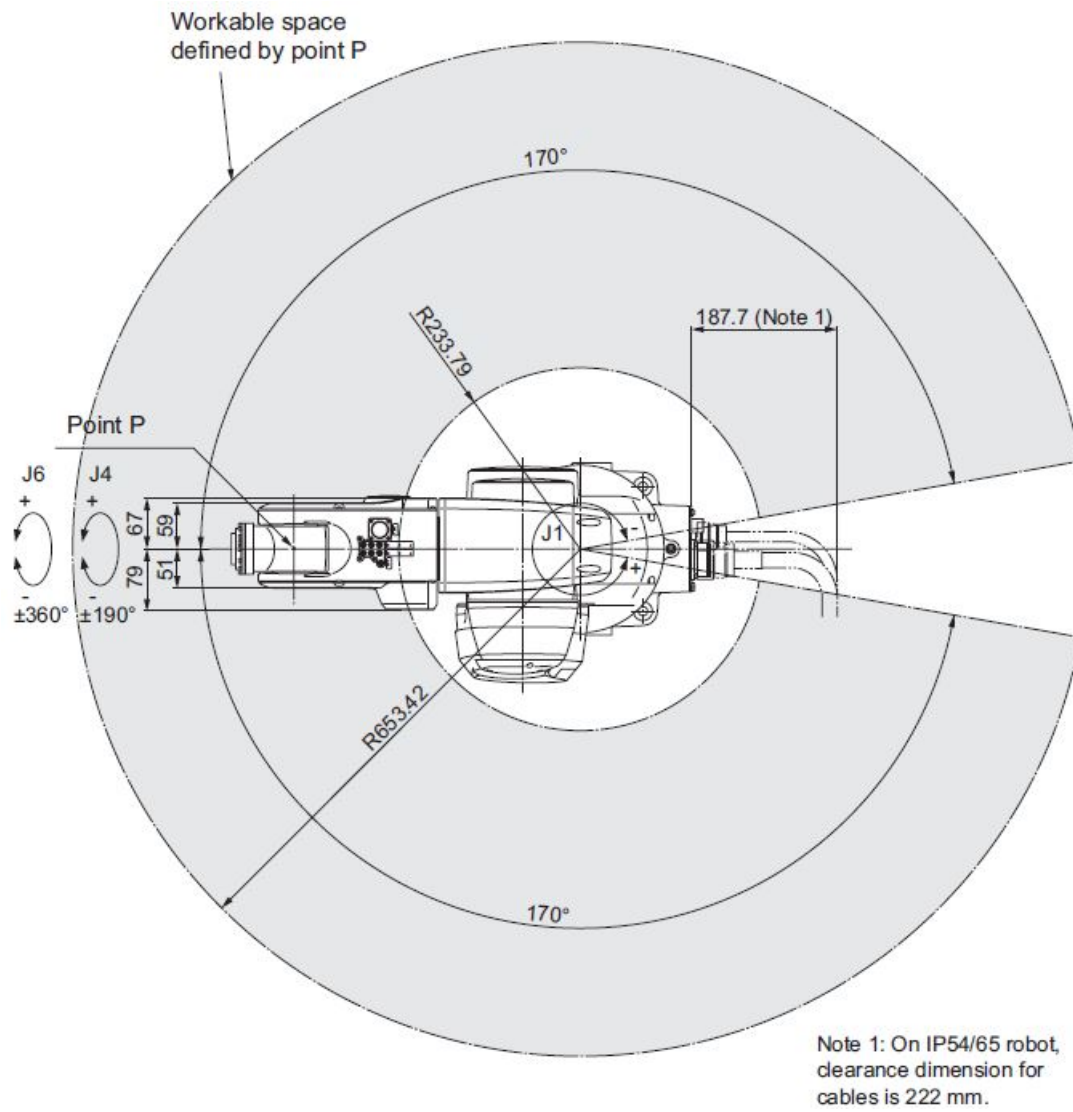


Figure D.2: Adept Viper s650 Top Dimensions and Work Envelope [40]

