Pre-Study

Project name	Client / Sponsor	Project managers
Microwave Imaging	Nikola Petrovic	**Software Manager:** Victor Aziz **Hardware Manager:** Emanuel Bjurhager

1 Mission

1.1 Background

Breast cancer is the one of the most common types of cancer and which dominantly affects women. Around 30% of the diagnosed cancer among women is breast cancer, and in Sweden alone, according to the Swedish cancer society, approximately 20 women get diagnosed with it every day [1]. Often, the cancer is close to symptomless in its preliminary stages, making it hard to detect. But if found early, the likelihood of eliminating the cancer is high. Commonly, breast cancer is found with mammography [2], where X-ray images are taken of the breast. This process requires the breast to be compressed, which may feel uncomfortable or cause pain for the patient. The X-ray used in mammography exposes the patient to ionizing radiation, which, while being tiny doses, still pose as a potential risk for the patient. Mammography has limited capacity in identifying tumors without a characteristic mass, often seen in lobular breast cancer or tumors without calcification [3]. Other solutions, such as MRI and ultrasound, also have limitations. Therefore, there is a need for novel solutions that can detect breast cancer early.

to Microwave tomography (MWT) is a biomedical imaging technique where microwaves are used to illuminate a target from multiple angles and where the collected data is used to create cross-sectional images. Microwave imaging makes it possible to detect cancerous tumors as healthy and cancerous tissue respond differently to electrical fields in the microwave spectrum, making them distinguishable from one another in the produced images. MWT poses as a potential competitor to mammography, as it is non-intrusive, comfortable and without ionizing radiation, making it suitable for both detection and recurrent monitoring during treatment [3].

Innovation and development in the field of MWT is the focus of an ongoing project at Mälardalens University. In a previous study [4], a robot-controlled data acquisition system for microwave imaging was developed and validated. The system comprised a robotic arm, two monopole antennas, a water tank in which the object to be scanned and the antennas were placed, and a MATLAB interface for controlling the data acquisition. During the scanning, both the transmitting and receiving antennas would be immersed in the water tank, where the transmitting antenna was in a fixed position while the receiving antenna was fixed to the robotic arm, which could move along the surface of the object in a pre-programmed pattern. Because the receiving sensor only moved in a pre-programmed pattern, with no consideration to the object's placement, the object itself had to be positioned in relation to the robot's coordinate system with high accuracy. When validated through comparison between measured and simulated data, the system showed promising results and reproduced symmetry was observed. Since then, different prototypes of arm designs have been developed and tested, and improvements to the transmitters have been made, making them suitable for a dry set-up where no water is used.

Three-dimensional (3D) reconstruction is a mathematical representation of a real-world object. 3D scanning and reconstruction have become important in the medical industry and is used to improve the treatment [5]. A method for 3D scanning will scan the surface of an object and generate a point cloud. A point cloud is a set of data point in space. The reconstruction method will use the point cloud to approximate the 3D surface of the object. The 3D model can be created with no physical contact with the object by using a non-contact sensor technology, such as LIDAR.

When working with data collected from practical applications, there will certainly be noise present in the data. Reconstruction of objects digitally is no exception and can make a representation look nothing like the actual object that was scanned if it is not dealt with [6]. Speckle noise and reflections are some of the largest contributors to the noise in image reconstruction [7]-[8]. Many proposed solutions to the problem have been tried, ranging from using filters on the signal to extract the desired data to smooth data using different mathematical functions [9].

1.2 State of the Art

A research group based at the University of Calgary [10] have successfully created a method for automatically scan for breast cancer. Their 3D reconstruction was done using a laser triangulation sensor mounted on a four degrees-of-freedom robotic arm, which measured the breast in the horizontal plane. The 3D scanning protocol was based on scanning the breasts at different heights in the Z-plane to get a representation of the contour at different angles in the X, Y-plane. The data collected was interpolated and then used to get an image of the entire breast. The breast reconstruction was then used to as a reference when controlling the robotic arm, which had a sensor for detecting anomalies in the breast tissue. The paper concluded that their surface reconstruction using laser triangulation was quick and successful.

Another research group [11] also works with breast cancer detection, but in contrast to the group based in Calgary, this 3D reconstruction technique uses a cheap webcam to estimate the surface of the breast. The camera took 12 pictures of the breast in the azimuth plane. By using edge detection, a curve of the breast contour could be approximated. This procedure was repeated around the Z-axis in 0.5mm intervals in the X, Y-plane. By combining all the breast contour estimations, a 3D surface could be estimated. The greatest surface error was 2mm compared to the real breast. However, the Z-axis was elongated, which caused the estimated position of a tumour to be off by abound 10mm.

The use of robotics in the field of medicine has seen an increase over the last decade. Their areas of application range from using the robots for normal checkups to being used in the surgical room to help the surgeon [12]. ABB is one of the world's leading companies in designing robotic arms that meets a high standard of precision. One example of such a robot is the YuMi robot being a seven axis robotic arm, the seventh axis giving it redundancy, resulting in the freedom of performing more complex movement than a six axis robot. The arm has a reach of around 56 cm mimicking a human arm, with a pose repeatability of 0.02mm [13]. The robot has been certified for use close to and in contact with humans and it even has been successfully implemented and used in the medical field like performing tasks as distributing medicine to patients [14].

A multitude of different hardware and software setups for microwave imaging have been developed since the technology first emerged. In the early 2000s Meaney et al. [15] were one of the first to develop a clinical prototype for microwave imaging of a breast. The system comprised 16 monopole antennas arranged in a circular array configuration, where the antennas were submerged in a saline bath, and the patient was laid on a table above the tank with the breast hanging into the fluid. Since then, a large quantity of systems have emerged with similar designs. Using multiple transmitters in a circular array could still be regarded as state-of-the art today [16], since it is still used by the Wavelia system.

The Wavelia system [17] is a microwave breast imaging device developed by MVG Industries, currently under clinical investigation. Similarly to the system developed by Meaney et al., the Wavelia system also comprises multiple antennas arranged in a circular array, where the patient lies prone on a table with the breast hanging into the coupling fluid. But the new system differentiates itself by using 18 equally spaced wideband Vivaldi-type probes, placed outside of the cylinder that contains the fluid. These probes are rotated vertically around the breast, illuminating it in 5mm intervals. The microwave breast imaging system is also paired with an optical breast contour detection (OBCD) system. The OBCD system allows the external surface of the breast to be reconstructed and the breast volume to be calculated with the help of a 3D stereoscopic camera, placed below the examination table. As of now, the system has shown excellent results, both when detecting dielectric contrast between tumor phantoms and synthetic breast models, and in clinical studies with human subjects. However, the current generation of the system cannot detect lesions less than 10mm, and is unsuitable for patients with smaller breasts, as the breast must have enough mass to create a pendulous reach when lying prone. The system is also limited in detecting abnormalities near the underlying chest muscles, as there is 2-4cm between the uppermost scanning position and the chest wall. Using coupling fluid is also not preferred because it is can be seen as unhygienic and requires the patient to clean their breasts after examination.

1.3 Purpose

The purpose of this project is to help the stakeholders take their research further and closer to clinical trials. In extension, their research purpose is to discover and invent new techniques for finding breast cancer in an early stage without exposing the patient to ionizing radiation.

1.4 Goal

The goal of this project is to do the following:

- Built a system that makes it possible to move the microwave sender up and down below the nipple of a breast replica.
- Acquire hardware for a robotic system that can move a receiver around an breast replica.
- Implement a system that can estimate the breast surface.
- Develop a graphical user interface to control the measurement system.
- Implement a system that can run a pre-defined measurement sequence.
- Fulfill the requirements.

1.5 Scope

SUBJECT	TYPE	FINISH DATE
Prestudy	PHASE	2022-09-15
0.0 - Pre-study Report	TASK	2022-09-15
Planning	PHASE	2022-09-30
1.0 - Project Plan	TASK	2022-09-30
Execution	PHASE	2022-12-16
Poster	TASK	2022-10-07
2.0 - Progress report: 1	TASK	2022-10-28
2.1 - Peer-Review: 1	TASK	2022-11-04
3.0 - Progress report: 2	TASK	2022-11-25
3.1 - Peer-Review: 2	TASK	2022-12-09
Final Poster	TASK	2022-12-09
Project Presentation	MILESTONE	2022-12-16
Hardware	TASK	2022-12-16
Robot "Arm"	TASK	2022-12-16
Small robot "Arm"	TASK	2022-12-16
End effector reciever	TASK	2022-11-04
End effector sender	TASK	2022-11-04
Software	TASK	2022-12-16
3D reconstruction algorithm	TASK	2022-12-16
GUI	TASK	2022-12-16
Scan path planner	TASK	2022-12-16
Data acquisition / processing	TASK	2022-12-16
Closure	PHASE	2023-01-13
4.0 - Project report	TASK	2023-01-13
GitHub handover	TASK	2023-01-13

Figure 1: WBS of project

1.6 Limitations

To avoid creating false expectations among the various stakeholders, the constraints are divided into two categories. The first category consists of the following:

- The team **won't** produce a finished product.
- **No** patient beds will be delivered under the project.
- **No** physical control panel will be delivered as part of the project.
- The team **won't** be working on the microwave imaging antenna technology.
- Humans will **not** be used in the product's testing.
- It **cannot** be guaranteed that all breast forms, sizes and colors works equally well.
- The finished product **lacks** a certification for either human or medical usage.
- The product does **not** have any form of energy saving.
- The product **lacks** a certification for EMC and EMI.
- It is **not** guaranteed that the product is safe.

The second category will discuss the key factors of the fundamental limits of this project. The project's budget, deadlines, the scope/project plan, required resources, and, last but not least, the project's quality all need to be taken into consideration. The budget is capped at about 20,000 SEK, although it might be increased if required. The project's timeline is constrained to begin on August 29, 2022, and must be handed over by January 13, 2023. The project's most important components are specified within its plan and scope, and in general, good project management equals excellent results. In other words, the project's management and careful planning are the team's initial focus. Many dangers can impact the project. Many hazards, such as depleted resources, operational blunders, poor performance, ambiguity, component shortages, and high expenses, may be encountered. When all these restrictions are considered, the project's final quality may be altered in a positive or negative way.

2 Requirement specification

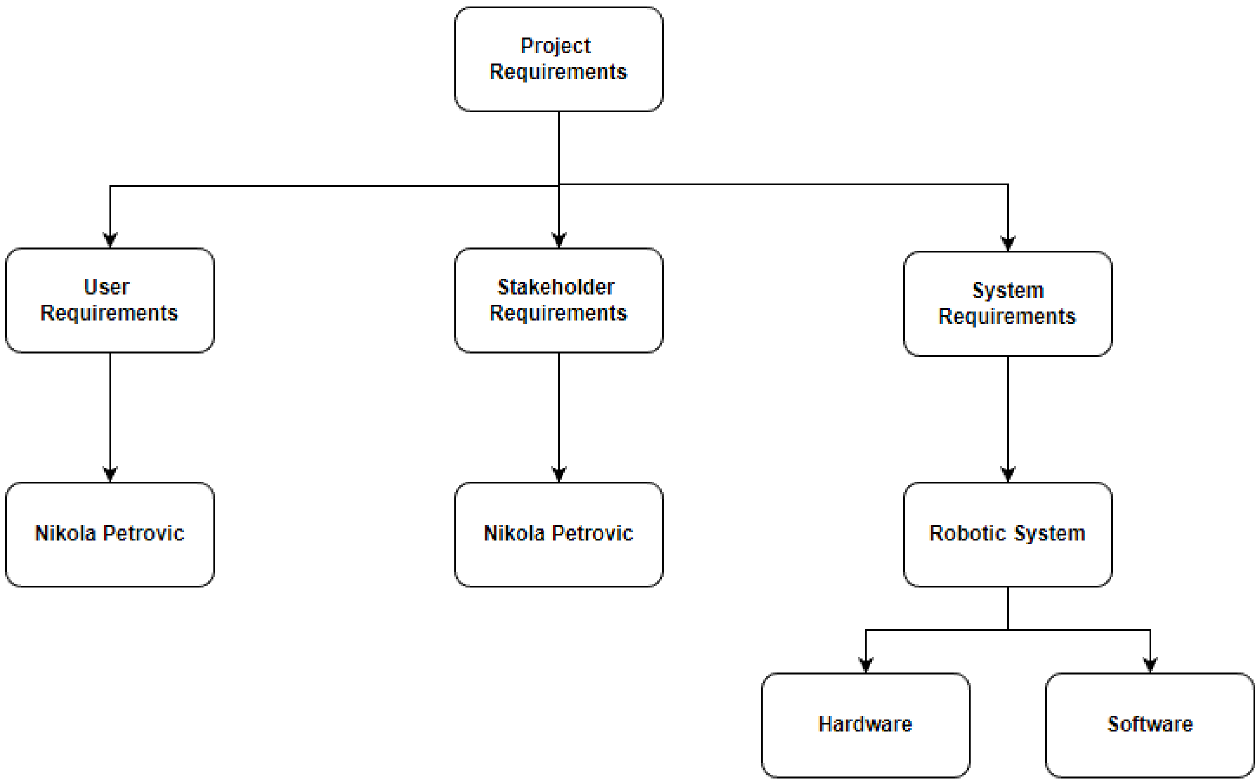

Figure 2: A simple requirement tree that shows what requirements the project has. The project requirements can be divided into three categories User, Stakeholder and system requirements. All categories will be discussed in the following subsections.

2.1 Product requirements

The system demands and prerequisites for achieving the project goal are the product requirements. The system comprises hardware and software components that work together to construct it. Each component of the system has requirements that will be covered separately in the following subsections.

2.1.1 Hardware requirements

The hardware can be divided into multiple subsystems: receiver end effector, sender end effector, receiver robot arm and sender robot arm.

- The receiver end effector must contain the microwave receiver, at least one accurate (± 1mm) distance measurement sensor and some way of making sure that the end effector is always roughly normal to the breast.
- The sender end effector must contain the microwave sender.
- The receiver robot arm must be able to place the microwave receiver normal to the breast at any location at a distance of 0mm to 10mm, except around the nipple region where the sender is. The receiver robot arm must have an accuracy of ±0.5 mm. It must also be resistant to minor disturbances.
- The sender robot arm must be able to place the microwave sender at any distance (0mm to 10mm) from the nipple region of the breast. The sender robot arm must have an accuracy of ±0.5 mm. It must also be resistant to minor disturbances.

2.1.2 Software requirements

The software can be divided into the following subsystems: 3D reconstruction, planning, GUI and data acquisition.

- The 3D reconstruction algorithm must be able to estimate the breast surface based on the measurement data provided by the sensor(s).
- The planning algorithm must be able to calculate at what locations and in what order the receiver robot arm must stop to let the microwave receiver take measurements, based on configurations done in the GUI by the user. The algorithm also need to make sure the receiver robot arm does rotate many turns around the breast as this will damage the cables.
- The GUI must display information about the system and let the user configure the scanning region, distance, and density.
- The data acquisition must store the sensor readings to aid further development of the system.

2.2 User requirements

Because the stakeholder will be the user, the user requirements and the stakeholder requirements are the same.

2.3 Stakeholders requirements

These specifications outline the needs and expectations of the stakeholders for this project.

- The measurement process should be automatic.
- There should be a way to mount the microwave antennas on the robotic arms.
- The distance between the breast and sender/receiver should be controllable using the GUI.
- The receiver needs to be normal to the breast while scanning.
- The scanning system should work with simple and more complex shapes, such as cylinders, semi-spheres and breast replicas.
- The system must have a GUI such that the user can change the scanning region, scanning density and the distance between the antennas and the breast.
- The receiver must be able to move to almost any location around the breast, except where the sender is, and where the ribs are.
- The positioning accuracy should be $\lessapprox 1$ mm.

3 Proposed solution

Our proposed solution does not cover all the problems of the project yet. The solution covers some overarching problems and addresses some of the possible solutions for the rest of the problems.

A single-armed Yumi with 7 degrees of freedom is provided from ABB. Yumi robot arm is a state-of-the-art solution for the problem of moving the microwave imaging sensor and scanning sensor in 3 dimensions while also imposing an end-effector orientation.

A single-armed Yumi has already solved a lot of problems and given us the possibility to focus on other problems. The system consists of 4 major parts and every part has its problem and solution. The solution for scheduling and communication between different parts will be discussed in the future.

3.1 Scanning an object and acquiring data.

The solution is to equip yumi with a sensor that will scan the object. The sensor type is not decided yet as there are different alternatives with different pros and cons. The choice of the sensor is based on what type of data is needed for the surface reconstruction algorithm. Currently, we have limited the sensors to 3 different sensor solutions to scan an object.

- Firstly a laser scanner may use triangulation or time of flight to detect the distance to the object. There are many laser choices with different qualities and prices. The lasers can be equipped with different beam types that can be multiple beams or lines. There are 2 types of approaches for the lasers. The first approach is to use multiple cheap lasers that provide a lot of data but also a lot of noise. The second approach is to use one high-quality laser sensor that provides fewer data points but more accurate data with less noise.

- The second solution is to use a camera and take multiple pictures of the object by following a picture alignment protocol. Studies have shown that the laser is more accurate than the camera solution.

- A third solution is to use a combination of laser and camera to get the most out of both technologies.

3.2 Surface reconstruction using the acquired data.

That part of the project is under discussion as there exist a lot of algorithms to solve this problem. They all have advantages and disadvantages and different algorithms need different types of data and also different quantities and quality of data. We can more easily decide the type of sensor needed to scan the data after a decision is made on what algorithm to use for surface reconstruction.

As a summary for the discussion about the existing solutions, Delaunay Triangulation and Voronoi Diagram work well for noise-free data. In our case, the millimeter accuracy required makes it difficult to be able to consider our data noise-free as sensors will always have some type of uncertainty.

Another more accurate algorithm exists as the Poisson algorithm which requires the normal vectors of the data points. The object's location is unknown at the start and the normal vectors cannot be provided directly by the sensor. Some other algorithms try to make the Poisson algorithm work without normal vectors. Those algorithms and the algorithm that include both a camera and laser sensor are still under research.

3.3 Automated Microwave measurements

If the reconstruction algorithm is accurate enough to fulfill the requirements, the problem of this part is almost solved. The single-armed yumi provided by ABB has pose repeatability of 0.02 mm. It will not be a problem to achieve an accurate location from the object if the object's shape and position are known. Until now we were not able to find a surface reconstruction algorithm accurate enough. The best algorithm is the combination of camera and laser data but this solution will have a high complexity and computation cost.

A discussion is ongoing on the type of solution we can have for this problem. One of the ideas is to equip Yumi with extra sensors that will provide feedback control about the object location for the adjustments of the error. Research is ongoing on this topic to find what solution works best.

3.4 Grafical user interface.

On top of all parts of the system, there should be a graphical user interface that will provide communication between the user and the system. It should also provide configuration for the system developer to make it easier to acquire data and test the system.

In the initial scanning section, the graphical interface will help the developer choose a scanning protocol for the unknown object. This helps test different protocols with different amounts of data. The GUI also interactively shows the reconstruction results. In the microwave measurements phase, the interface uses the interactive surface to select points or regions to scan.

The solution discussed in this part is to use Matlab application designer as it is easy and has enough features to create the GUI. Matlab app is chosen as it is expected to use Matlab as a main interface for the whole system and will be easier to use their interface solution. If the choice of main developments changes to Python or something else the choice of GUI will be reconsidered.

4 Planning

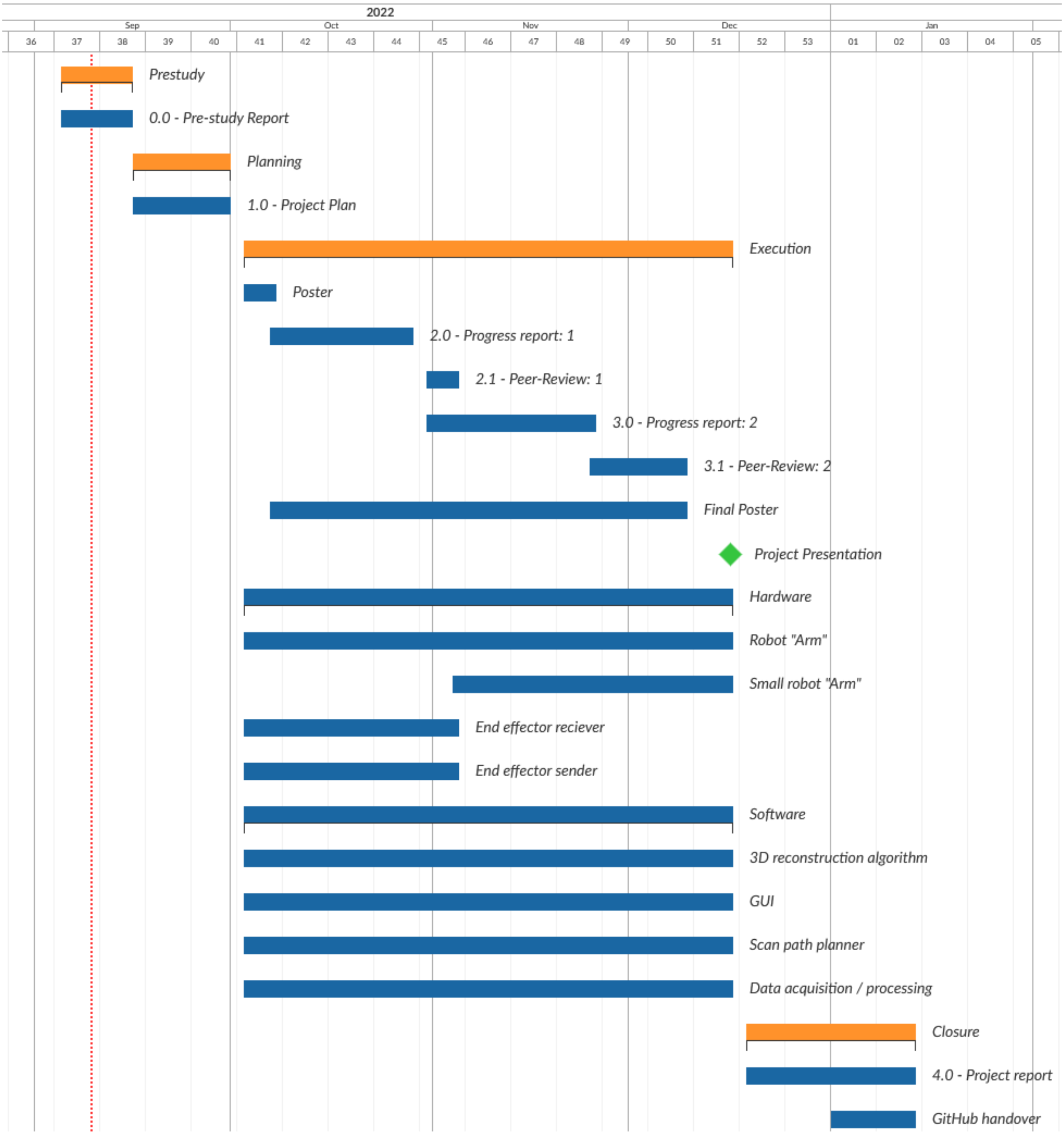

Figure 3: Gantt chart of the project.

5 Staffing

- Victor Aziz - Software Manager
- Emanuel Bjurhager - Hardware Manager
- Amanda Rautio - Software Member
- Ingrid Heien Bjonge - Software Member
- Jonathan Holm - Software Member
- Aref Bahtiti - Hardware Member

References

[1] A. Helena Torsler and N. Loman, *Bröstcancer*, Cancerfonden, [Online] Available: `https://www.cancerfonden.se/om-cancer/cancersjukdomar/brostcancer`, 2021.

[2] S. Susanna, *Mammografi*, 1177, [Online] Available: `https://www.1177.se/Vastmanland/behandling--hjalpmedel/undersokningar-och-provtagning/bildundersokningar-och-rontgen/mammografi/`, 2020.

[3] T. Rydholm, 'Experimental Evaluation of a Microwave Tomography System for Breast Cancer Detection,' En, Ph.D. dissertation, Chalmers University of Technology, Gothenburg, 2018. [Online]. Available: `https://research.chalmers.se/publication/505529/file/505529_Fulltext.pdf` (visited on 07/09/2022).

[4] N. Petrovic, T. Gunnarsson, N. Joachimowicz and M. Otterskog, 'Robot controlled data acquisition system for microwave imaging,' p. 5,

[5] A. Haleem, '3D scanning applications in medical field_ A literature-based review,' en, p. 13,

[6] Y. Cui, S. Schuon, S. Thrun, D. Stricker and C. Theobalt, 'Algorithms for 3d shape scanning with a depth camera,' *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 35, no. 5, pp. 1039–1050, 2013. DOI: `10.1109/TPAMI.2012.190`.

[7] C. K. Rekha, K. Manjunathachari and G. V. S. Rao, 'Speckle noise reduction in 3d ultrasound images — a review,' in *2015 International Conference on Signal Processing and Communication Engineering Systems*, 2015, pp. 257–259. DOI: `10.1109/SPACES.2015.7058260`.

[8] V. Kumar, A. Kumar Dubey, M. Gupta, V. Singh, A. Butola and D. Singh Mehta, 'Speckle noise reduction strategies in laser-based projection imaging, fluorescence microscopy, and digital holography with uniform illumination, improved image sharpness, and resolution,' *Optics & Laser Technology*, vol. 141, p. 107 079, 2021, ISSN: 0030-3992. DOI: `https://doi.org/10.1016/j.optlastec.2021.107079`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0030399221001675`.

[9] P. Craven and G. Wahba, 'Smoothing noisy data with spline functions,' *Numerische mathematik*, vol. 31, no. 4, pp. 377–403, 1978.

[10] D. Kurrant, J. Bourqui and E. Fear, 'Techniques for breast surface reconstruction with applications,' in *2016 17th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM)*, 2016, pp. 1–3. DOI: `10.1109/ANTEM.2016.7550205`.

[11] J. M. Felicio, J. M. Bioucas-Dias, J. R. Costa and C. A. Fernandes, 'Microwave breast imaging using a dry setup,' *IEEE Transactions on Computational Imaging*, vol. 6, pp. 167–180, 2020, ISSN: 2333-9403, 2334-0118, 2573-0436. DOI: `10.1109/TCI.2019.2931079`. [Online]. Available: `https://ieeexplore.ieee.org/document/8777154/` (visited on 05/09/2022).

[12] C. D'Ettorre, A. Mariani, A. Stilli *et al.*, 'Accelerating surgical robotics research: A review of 10 years with the da vinci research kit,' *IEEE Robotics & Automation Magazine*, vol. 28, no. 4, pp. 56–78, 2021. DOI: `10.1109/MRA.2021.3101646`.

[13] *Yumi® irb 14050*, ABB, Mar. 2021.

[14] ABB, *Abb demonstrates concept of mobile laboratory robot for hospital of the future*, New ABB, Oct. 2019. [Online]. Available: `https://new.abb.com/news/detail/37279/hospital-of-the-future`.

[15] K. Paulsen, S. Poplack, Dun Li, M. Fanning and P. Meaney, 'A clinical prototype for active microwave imaging of the breast,' *IEEE Transactions on Microwave Theory and Techniques*, vol. 48, no. 11, pp. 1841–1853, Nov. 2000, ISSN: 00189480. DOI: `10.1109/22.883861`. [Online]. Available: `http://ieeexplore.ieee.org/document/883861/` (visited on 06/09/2022).

[16] S. Lee and S. Kwon, *Recent Advances in Microwave Imaging for Breast Cancer Detection*, English, 2016. [Online]. Available: `https://www.researchgate.net/publication/312244309_Recent_Advances_in_Microwave_Imaging_for_Breast_Cancer_Detection` (visited on 05/09/2022).

[17] B. M. Moloney, P. F. McAnena, S. M. Abd Elwahab *et al.*, 'Microwave Imaging in Breast Cancer – Results from the First-In-Human Clinical Investigation of the Wavelia System,' en, *Academic Radiology*, vol. 29, S211–S222, Jan. 2022, ISSN: 10766332. DOI: `10.1016/j.acra.2021.06.012`. [Online]. Available: `https://linkinghub.elsevier.com/retrieve/pii/S1076633221002993` (visited on 07/09/2022).