Progress Report 2-µTomography

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I. Project Information

Project title	Client Sponsors	Project Team Leaders	Project Date
Microwave Imaging for Breast Cancer Detection: A Non-Contacting Approach	Nikola Petrovic and Cristoph Salomon	**Software**: Märta Krönström **Hardware**: Dennis Landré	2023/12/04

Name	Title	Responsibilities
Dennis Landré	Hardware Team Leader	Ensuring the project meets hardware requirements. 3D Modeling.
Ihsan Haidari	Hardware Developer	Responsible for the platform and sender platform.
Märta Krönström	Software Team Leader	Ensuring the project meets software requirements. Responsible for simulations.
Joel Josefsson	Software Developer	Responsible for the Laser and distance measurements. 3D scanning patterns and Git.
Filip Lindhe	Software Developer	Responsible for the surface reconstruction
Jiantao Shen	Software Developer	Responsible for the GUI
Samuel Wågbrant	Software Developer	Responsible for YuMi and control systems.

II. Short project progress summary

This project is still on track, and so far there have been no big obstacles encountered. There are a few delayed work packages, but nothing that will prevent the progress of the project. Eight out of eleven work packages are completed and resources are now allocated to completing the three remaining work packages. Looking at the planned scope of the project, the team is on the last part of the goal to automate measurements for an object with known geometry. The plan is to start testing the complete system with the microwave sensors.

As development draws near completion, the main focus will be to improve laser and microwave measurements for the known object as much as possible. If the time frame of the project allows for it, measurements will be taken and improved for the unknown object as well.

The software team is currently working on implementing all the functionality into the Graphical User Interface (GUI), attempting to get the dynamical collision avoidance working, and improving already working parts. The hardware team is done with most of their parts and is currently working on 3D-printing some last things, helping out where it is needed for the software, and performing different measurements.

In the previous progress report, there were concerns about the calibration of the robot arm and it was identified as a potential risk. This risk has now been resolved and an acceptable accuracy has been achieved.

III. Work Package Status

The following section outlines the current status of the work packages, see Table I, specified in the project plan, see Appendix B. The section summarises the progress made since the previous progress report, completed 2023-10-30. The previous progress report can be seen in Appendix A.

Table I
This table outlines the status of each work package together with the date when each package should be completed.

ID	Work package	Deadline	Planning Status	Completion Status
1.1.1	Robot arm	17/9-23	Off track	In Progress
1.1.2	Platform	17/9-23	Off track	Completed
1.1.3	Sender platform	31/10-23	On track	Completed
1.1.4	Robot tool/end-effector	1/10-23	Off track	Completed
1.1.5	Breast phantoms	1/10-23	On track	Completed
1.1.6	Central control system	15/10-23	Off track	Completed
1.1.8	GUI	5/11-23	Off track	In Progress
1.2.2	Microwave measurements	3/12-23	On track	In Progress
1.2.3	Surface reconstruction	14/12-23	On track	Completed

A. 1.1.1 Robot arm

This work package is currently off track. This is mainly due to issues regarding the accuracy and calibration of the robot. The remaining work of this work package includes enhancing the robot's accuracy to improve object reconstruction, adding collision avoidance functionality to improve safety and system testing.

1) Calibration: During testing of the robot arm, it was discovered that it lacked the desired submillimeter precision. This was discovered by aiming the laser, mounted on the robot arm, towards the ceiling of the frame and moving in a circular pattern whilst having a constant z-value (height) in the software. The resulting laser values showed a difference of up to 10 mm between measurements depending on the working range[1], a larger working range resulted in a higher error. During these tests, it was ensured that the base of the robot and the ceiling of the frame were parallel to each other. After these tests, the robot arm was sent to ABB where they performed an Absolute Accuracy Calibration (AbsAcc). During the calibration, ABB technicians saw that the first and sixth axes on the robot had some rotation and translation problems which might have been the main issue with our earlier calibration tests.

Based on this we were advised to create a work object[2] and Tool Center Points (TCP)[3] from the robot controller to compensate for this.

A script was written to calibrate the axis rotations of the work objects coordinate system. It takes laser measurements on the platform's roof in a circle around the centre point with the same z-value. Then rotates the work object around the vector that is orthogonal to the vector between the highest and lowest points by a fraction of the angle between the same points in height.

A second calibration script was also written which takes three laser measurements in a right-angled matter and creates a plane from those three points using vector algebra. After the plane has been computed the quaternions of the plane can be calculated. The quaternions are then used to rotate the work object. This script is looping until a satisfactory difference in the three points' Z coordinates is observed.

Another script has been made that takes laser distance measurements of the nipple area from below to find the lowest point of the breast phantom. It takes points with equal distance from each other in a small square and points the laser straight upwards to take measurements. These values are then used to calibrate the centre point of the work object.

2) Simulations and collision avoidance: The following methods have been tested for dynamical collision avoidance:

Collision sets: It was possible to define collision sets by defining two objects that could not collide [1]. This would give an indication while simulating as shown in Figure 1, but could not be transferred into code. It was a helpful feature for simulations.

Collision free path: By picking two targets or move instructions (e.g. move linear instruction) and defining obstacles an automatic path could be generated [2]. This is shown in Figure 2. The issue with this method was that the path for the robot needed to be defined in the

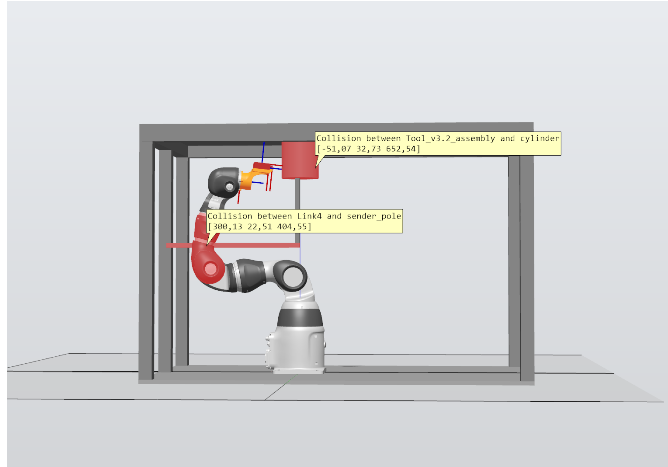

Figure 1. Collision sets. In this simulation, the tool is colliding with the cylinder representing the breast phantom and the arm is colliding with the sender pole. The indications are shown in the yellow boxes.

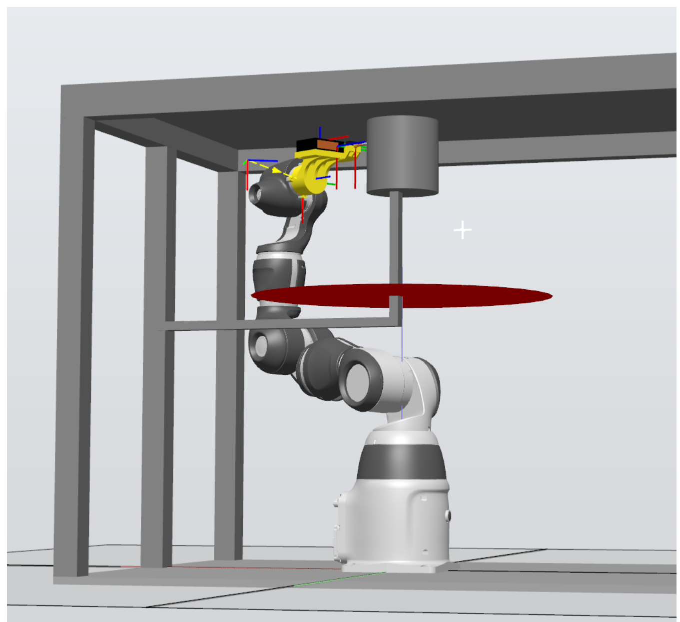

Figure 2. Collision free path. In this simulation, the red cylinder plane was added as an obstacle to achieve a circular collision free path. Further, two joint targets were created, which are displayed as small coordinate systems (the robot arm is located at one of them). Here an automatic path was created between the two targets, avoiding the obstacles.

simulation and the user could not input new points for the path during run-time. Based on obstacles in the simulation an automatic path was generated, but the function for generating this could not be accessed from the code (only in the RobotStudio simulation environment). If the user defines the targets and the obstacles and uploads this to the robot controller it works on the real application, but not if the user wants to give dynamical inputs.

Visual safe move: This method, shown in Figure 3, was recommended by an employee of the ABB test lab. Using this it would be possible to define different safe zones, and

[1]Working range is the area surrounding the robot which is reachable by the robot end-effector

[2]A work object is a transformation of the base robot coordinate system

[3]The TCP is the position of the mounted tool relative to the end-effector plate of the robot. When given coordinates, the robot will move the TCP to the coordinate.

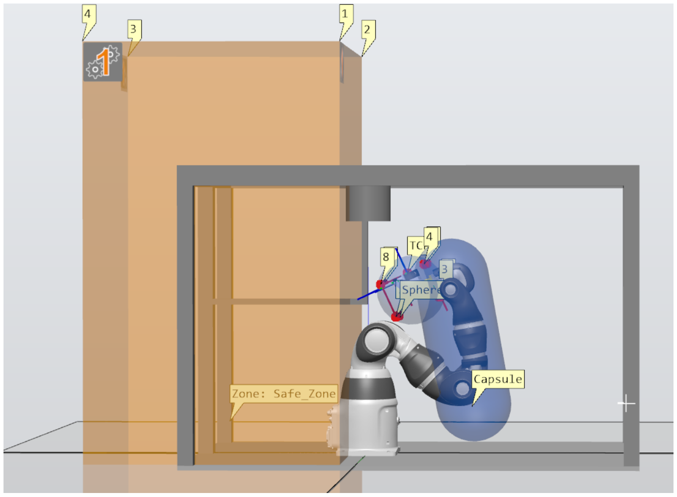

Figure 3. Visual safe move. Here one safe zone is defined, and the tool and robot arm are capsuled.

then the robot could slow down or stop if it enters the zones [3], [4]. This can also be uploaded to the controller, meaning that the zones will be known to the robot arm for the real application. This method had several problems. At first, the features for safe move were not available in RobotStudio, but this could be fixed by adding them to the configuration for the controller. Another issue with this method is that it is not sufficient to use by itself as it will not be able to automatically generate a new path if a collision is about to happen. At most, this could help to stop if the robot arm is about to collide. Another limitation of this method was that only one safe zone could be defined using the basic version, which was not enough. Another concern was that it is not visible as an add-in on the real controller, meaning it might not apply to the real application.

Zones combined with different configurations and joint limits: Another concept that was attempted was using different configurations for the robot arm in different zones. The issue with this was the complexity of it. The robot arm could have many different configurations (values of the joints) in each zone and found all configurations by trial and error. Also, it could enter parts of a zone, but not all of it. There are four different zones defined as mentioned in the previous progress report. If only the configuration is used then it will only allow to change axes 1, 2, 4 and 6, so not all of them. Another way was to define limits for each joint in each zone, but it led to the same problem as the previously mentioned one with too many possible combinations.

Smart components: Using this method, smart components in the form of two different types of sensors were defined [1]. Volume sensors; Volumes surrounding objects are created as shown in Figure 4, and the sensor is triggered if the robot gets within this volume (partial hit). The output from the sensor changes a variable in the RAPID code.

Another type of sensor defined was the collision sensor;

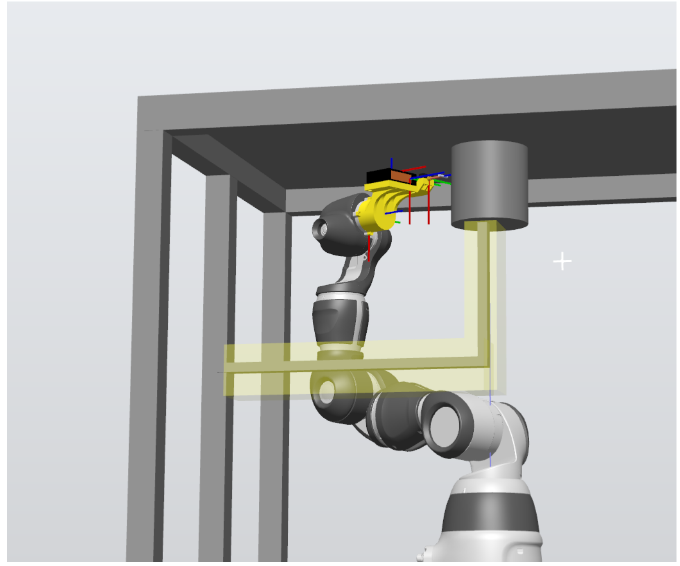

Figure 4. Smart components defined as volume sensors. In this simulation, the sender holder was protected using two volume sensors in yellow.

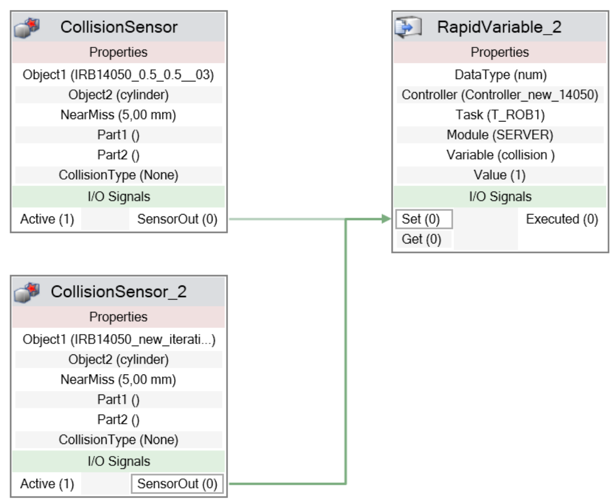

Figure 5. Smart components defined as collision sensors. Here two sensors are defined, one for the tool and one for the robot arm. The object they should avoid is the breast phantom (defined here as the cylinder).

this meant defining that the robot and the tool could not collide with certain objects in the simulation. Here the distance/sensitivity for the sensor could be defined, for example, 5 mm as shown in Figure 5. If a collision was about to happen, the sensor was triggered and similarly, a variable changed in the RAPID code. The problem with this method is what will happen when the sensors are triggered. Here the desired action is to be able to adjust and continue with the path if possible, but this would not happen automatically. Hence, a code for handling this was developed. The idea is to send a signal if a collision is about to happen, and then the robot would attempt to move to the next point instead.

This might mean that some points will be avoided, but it gives the possibility to continue. The main issue seems to be in relation to the synchronisation between sending and receiving the collision warnings.

3) Next steps: For dynamic collision avoidance, the collision sensors are what is currently being worked on. The problem with getting a fast response to the sensors and synchronisation is what is being looked into. More resources have been allocated for collision avoidance and they are looking into other possible options. Improvements to the already functioning parts are being worked on as well.

B. 1.1.8 Graphical User Interface

The GUI is currently off-track. Most of the features are completed. Big changes in the GUI and the features are based on newly completed functions, see Figure 6 and Figure 7 for the newest design. In addition, the system uses multi-threading to avoid freezing of the GUI. If the scanning was performed in the same main thread as the GUI, the GUI freezes until the scanning is completed. This meant the implemented stop button would be non-functioning. Thus, it will create a new thread when scanning to avoid this problem, When the user terminates the scanning thread with the stop button. There is still a remaining issue, the user is not able to perform scanning again after pressing the stop button. The reason could be that the system does not close the connection between the YuMi and Raspberry Pi when the scanning thread is terminated. The user can solve this by restarting the program. Therefore, this issue may be resolved in the future but is not a high priority.

The idea of the GUI is that when you press the scan button, the system will automatically connect the YuMI and the laser and perform scanning. The scanning is based on which tab is active and values on the spin box (a text box with up and down buttons for changing the value). In Figure 7, it shows *Auto Generate scanning point* tab and *Cylinder scan* tab are active. Therefore, it generates scan position list based on *circle_radius*, *z_stepsize*, *max_depth*, *offset*, *azimuthPoints* and *laser_angle* values and YuMI performed a cylindrical scan. Once the scanning is completed, the scanning points will be plotted on the chart and the result will be displayed on the "*Scanning result*" table. The 3D reconstruction will be displayed in a new window if you press the "*3D reconstruction*" button. You can stop the scanning by pressing the "*Stop*" button. You can also save and load the data in a file. Furthermore, you can create your own scan list by inputting x, y, and z values on the "*Scanning position list*" table. You can also move the laser to a specific point and point it at the model's surface. The calibration button is used to calibrate the origin of the system.

The manual control functions in the system are delayed. Because to move the robot arm to a specific position and face it to the surface of the object, coordinates are used for movement and quaternions are used for rotation. The quaternions are calculated by using mesh which is

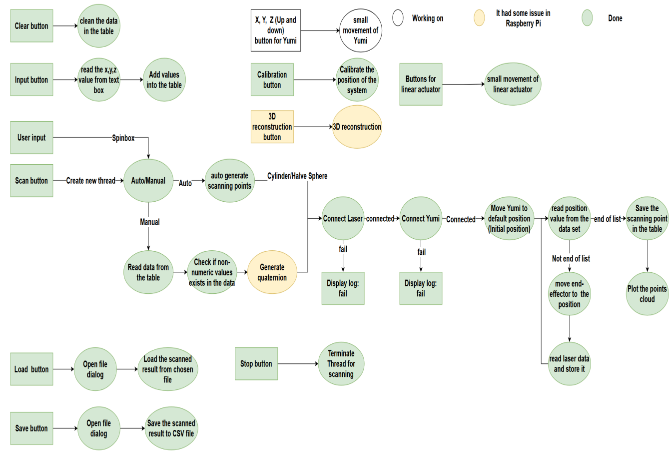

Figure 6. This diagram shows what features have been completed so far. The diagram has been updated and changed because of new completed functions and ideas. The white block is a feature for manual control of the YuMi. They are still in the "In progress" phase.

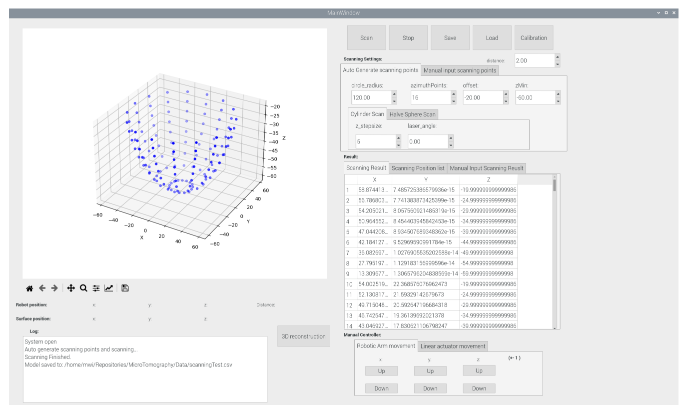

Figure 7. The figure shows the new updated UI design. Most of the changes are changes of position on some buttons and changing labels to fit the screen size of the Raspberry Pi. It was tested on Raspberry Pi. The result shown in the figure is a cylinder scan with automatically generated scan points.

generated by 3D reconstruction. 3D reconstruction is not working on the Raspberry Pi when connected to the GUI. Thus, manual control is delayed. Also, the manual control function of the linear actuator was added to the GUI.

1) Next step: The plan for the GUI is to complete all the functions in Figure 6 and test them on the Raspberry Pi as fast as possible. The main problem is that the 3D reconstruction does not work when added to the GUI. The remaining features use mesh data created through 3D reconstruction. When the problem is resolved, the GUI will be completed. Also, if there is still time, improvements to the GUI will be made.

C. 1.1.2 Platform

This package was off-track according to the last progress report. Since then all the equipment has been placed on it and cables have been managed, which was the things left

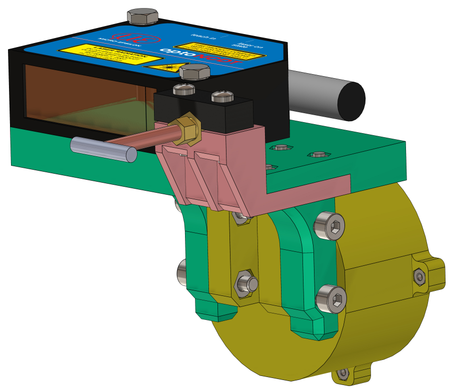

Figure 8. 3D model image of the new robot tool design with antenna and laser distance sensor mounted. The tool consists of three separate parts: base (yellow), platform (green) and receiver holder (pink).

to do. Now this package is complete.

D. 1.1.3 Sender platform

This work package is done. However, the sender platform is removed due to the need for testing of the whole system as it is in the way of the robot arm. The next step will be to attach the sender platform and its cable management.

E. 1.1.4 Robot tool/end-effector

This work package was off-track according to the last report. A new version of the robot tool, illustrated in Figure 8, has been designed and 3D-printed. The new design was 3D-printed as three separate parts, fastened together with screws into captive nuts. The main reason for this switch was the slight skew between important faces and undesirable aesthetics from the necessary supports needed to print the old version. The new version was designed with print accuracy in mind, meaning supports were avoided. The fitment between the parts is adjustable allowing for slight changes, most notably the angle between the cylinder base that mounts to the robot and the face on which the laser distance sensor mounts. The package is now considered complete.

F. 1.1.5 Breast phantoms

This work package is completed. Now, an asymmetrical breast phantom has been 3D-printed.

G. 1.1.6 Central control system

This package was considered off-track in the last progress report. Since then the laser distance sensor power supply, stepper motor driver, RS485 serial adapter, custom transistor switch circuit board, physical laser off switch, custom step-down circuit board and the Raspberry Pi with a 3D-printed mounting case and an integrated 40mm fan have been mounted in a 3D-printed case depicted in Figure 9.

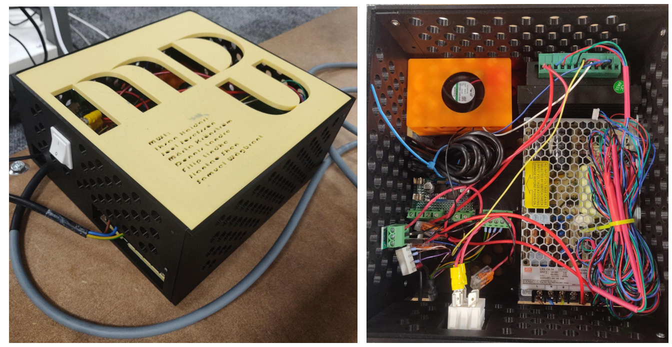

Figure 9. Central control system box from the outside (left) and inside (right).

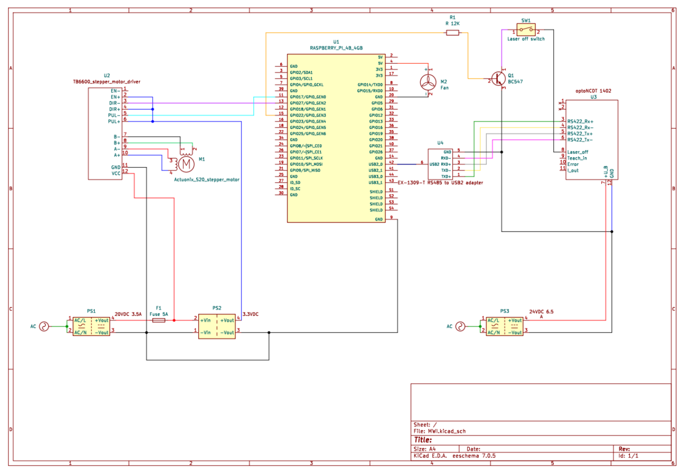

Figure 10. Central control system circuit diagram.

The system also has a corresponding circuit diagram shown in Figure 10. With this done, the work package is considered complete.

H. 1.2.2 Microwave measurements

The network analyser has been tested using no sensors or applicators connected with a library provided by the stakeholders written in Python. The next step is to test it with the real sensors together with the stakeholders. The measurements and tests with the complete system will start on Monday 27/11-23.

I. 1.2.3 Surface reconstruction

An error tracing algorithm was developed which uses ray casting as the main technique. It functions as follows. The function takes two inputs, the reconstructed mesh as well as the point cloud of a modelled CAD object. It then ray casts from each point in the modelled CAD object's point cloud, in the direction of the points normal. When the ray cast hits the reconstructed mesh it calculates the distance from the point cloud to the reconstructed mesh. Thus giving an error on how close the mesh is to each point in the CAD model's point cloud.

Another algorithm was developed using the same ray

Table II

TABLE SHOWING TEST DONE WITH 2 DIFFERENT DATASETS FOR BOTH THE COCONE ALGORITHM AND POISSON ALGORITHM. THE TABLE SHOWS THE RESULTS WHEN IT COMES TO AVERAGE, MIN, AND MAX ERROR. FROM THIS TABLE, IT IS CLEAR TO SEE THAT THE POISSON SURFACE RECONSTRUCTION ALGORITHM PERFORMS BETTER IN REGARDS TO DISTANCE ERRORS. HOWEVER, THE COCONE ALGORITHM COMPUTES FASTER.

Data	Algorithm	Average error (mm)	Max error (mm)	Min error (mm)	Time (s)
point cloud 1	Poisson	2.22	4.8	0.000495	0.26
point cloud 1	Cocone	4.78	14.1	0.000460	0.021
point cloud 2	Poisson	0.94	2.5	0.00134	0.25
point cloud 2	Cocone	5.76	23.5	0.000723	0.02

casting technique which takes three different inputs. The inputs are the reconstructed mesh, a list of points, as well as a distance in mm. The function's main purpose is to find points close to the mesh where the microwave antenna should be placed. The function ray casts from the list of points, when the ray cast hits the mesh it computes the point on the mesh it hits as well as the points normal. The function then adds the distance in mm in the direction of the normal and returns the new point which is where the microwave antenna should be placed. The function also calculates the quaternions of the new points normal which makes sure that the robot end-effector is rotated correctly in the same rotation as the normal.

After these two functions were developed two different data sets were sampled which in this report are called *point cloud 1* and *point cloud 2*. The data sets were then converted to meshes using two different algorithms, the Cocone algorithm and the Poisson surface reconstruction algorithm. In Figure 11 the results of the error tracing function can be seen when using the Cocone algorithm and in Figure 12 the results of the error tracing function can be seen when using the Poisson algorithm. The figures show the reconstructed mesh's point cloud in white and the CAD model's point cloud in colour. The colour indicates the distance from the CAD model's point cloud to the reconstructed mesh, giving us a good indication of how good the reconstructed mesh is, as well as where the errors are located. In Table II the results of the two different data sets can be seen. The results clearly show that the Poisson surface reconstruction is superior when it comes to reconstructing meshes using non-uniformed sampled data. However, it is worth noting that the time to reconstruct the mesh is significantly lower when it comes to the Cocone algorithm.

Figure 13 shows the results of the algorithm that computes the points where the microwave antenna should be placed. The red dots are the arbitrarily chosen points where the user wants the antenna to be placed, the algorithm then computes the green points which are the actual points close to the mesh where the antenna will be placed. The red arrows indicate the normals of the chosen points.

Figure 14 shows the reconstructed mesh using dataset *point cloud 2*. Since Poisson tries to create a watertight mesh we get some artefacts at the top of the mesh, this will cause no issues with the final results since the microwave

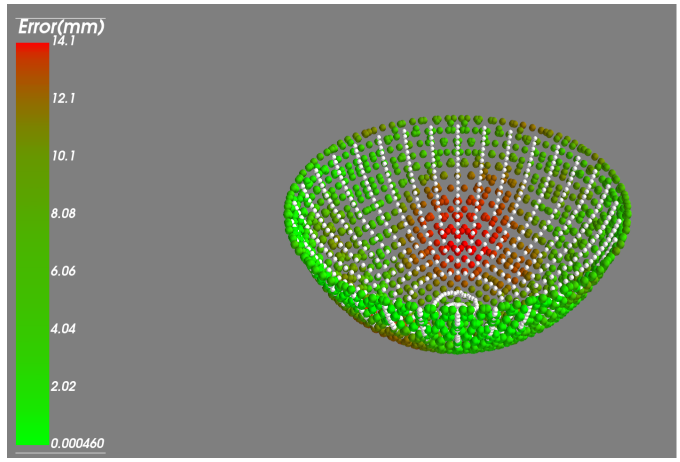

Figure 11. Error trace function showing the error (colour) of *point cloud 1* over the reconstructed object (White) when using Cocone surface reconstruction algorithm.

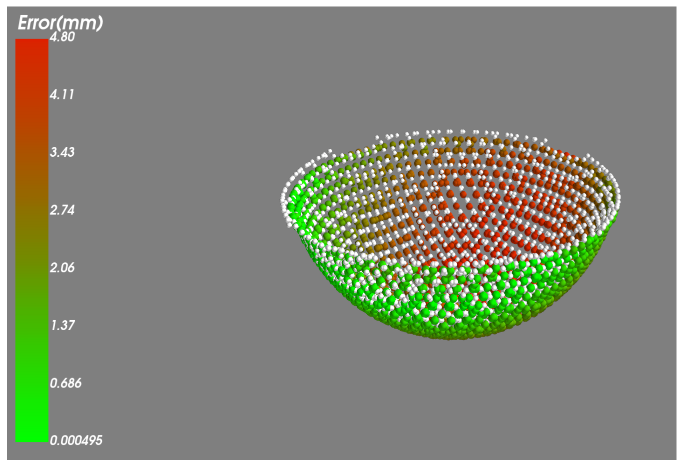

Figure 12. Error trace function showing the error (colour) of *point cloud 1* over the reconstructed object (White) when using Poisson surface reconstruction algorithm.

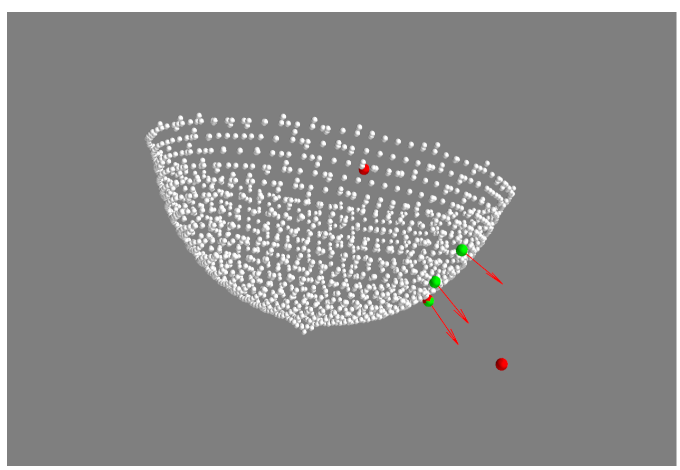

Figure 13. Figure showing the mesh (White dots) together with the arbitrarily chosen points (Red) and the points on the mesh correlating to the chosen points (Green) with their respective normal.

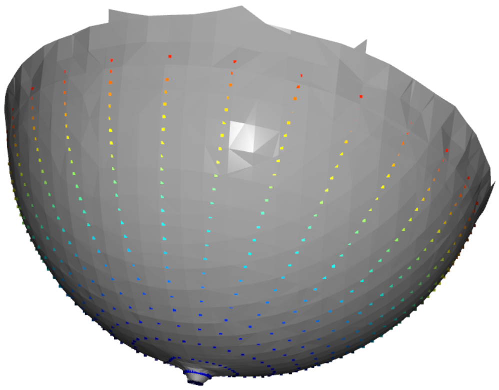

Figure 14. Surface mesh using Poisson surface reconstruction algorithm

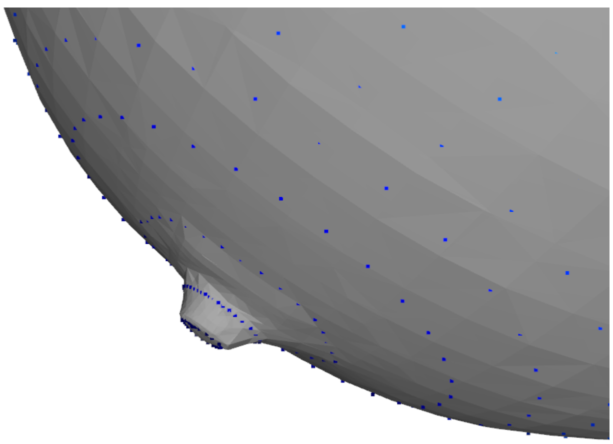

Figure 15. Surface mesh zoom in on nipple region using Poisson surface reconstruction algorithm

imaging will not be applied in that region where the artefacts arise. Figure 15 shows the same mesh but zoomed in on the nipple region which shows the level of detail which is currently achievable.

1) Next step: This work package is now complete.

IV. Completed Activities and Upcoming Activities

The following section details the completed activities and upcoming activities found in the project plan, see Appendix B.

A. Completed

The following list is based on the Work Breakdown Structure (WBS) seen in Appendix B and contains all the completed deliverables, work packages, and tasks. This means that if a work package is stated, all deliverables and tasks within it are completed (hierarchical order).

- 1.1.2 Work package platform
- 1.1.4 Work package Robot tool/end-effector
- 1.1.5 Work package Breast phantoms
- 1.1.6 Work package Central control system
- 1.1.8.1.1 Emergency stop button
- 1.1.8.1.2 Buttons for control of the robot arm in different coordinate systems
- 1.1.8.1.3 Task Buttons for control of sender platform
- 1.1.8.1.7 Task Visualisation of results
- 1.2.2.2.1 Task User can choose area
- 1.2.2.2.2 Scanning points based on given positions
- 1.2.2.2.3 Move transmitter and receiver to defined positions
- 1.2.3 Work package Surface reconstruction

B. Upcoming

The following list is also based on the WBS seen in Appendix B and includes the upcoming activities within the project.

- 1.1.1.2.2 Task Test inside of the frame
- 1.1.1.3 Deliverable Documentation
- 1.1.8.1.5 Buttons for control of microwave measurements
- 1.1.8.1.8 Task Controls with manual control similar to the joystick on the controller
- 1.1.8.2 Deliverable Documentation
- 1.2.2.2.4 Task Perform measurements
- 1.2.2.2.5 Task Save data
- 1.2.2.3 Deliverable Documentation

V. Accountability for Off-Track Work Packages

Work package 1.1.1 Robot arm is currently off-track, responsible for this work package are Märta Krönström and Samuel Wågbrant.

Work package 1.1.8 GUI is currently off-track, responsible for this work package is Jiantao Shen.

VI. Recovery Plan for Off-Track Work Packages

Many work packages that are not yet currently completed are in fact near completion. This entails that resources can be redistributed to accommodate for the delay of off-track work packages without compromising remaining work packages.

A. 1.1.1 Robot arm

Additional resources from the software team have been allocated to complete this work package. Resources from other work packages can be reallocated since many other work packages for the software team are either completed or are in the final stage and awaiting system integration.

B. 1.1.8 GUI

The GUI has been set off-track due to delays from other work packages. Additional resources were allocated to complete work packages which were blocking the GUI work package. This has opened up the workflow for the remaining work of the GUI work package to allow for its completion.

VII. Issues, Blockers and Risk Status

One blocker has been that the license server holding the school licenses for Robot Studio has been down occasionally. This has led to the software team being unable to use premium functionalities in Robot Studio during these occasions. The steps to mitigate this have been to communicate the problems to Daniel Morberg who is the owner of the license server.

Another blocker related to the licenses has been that working on different licenses for different versions of Robot-Studio has not been possible since they are not compatible. There is not so much to do about this, but to minimise future problems or blockers relating to this, the same license has been used for all group members.

One issue we currently have is still the calibration. Even though we have made significant improvements in the calibration, it is still not perfect. This is reflected in the surface reconstruction where the reconstructed breast seems to be shifted slightly. This calibration related inaccuracy stems from trying to find the lowest point on a symmetric breast phantom which has a small gradient change. There is a possibility that the lasers own inaccuracy can aggravate the calibration when dealing with minor changes in distance. One potential solution is to design another calibration tool that has a steeper gradient with a clearly defined point at its centre.

VIII. Individual Contributions

A. Ihsan Haidari

I have been working with both hardware and software, mostly trying to find a way to avoid collision between robot and platform. This includes methods such as safemove, forbidden zones, collision avoidance, etc.

B. Joel Josefsson

Have been working on the robot arm control. Made one of the calibration scripts and a script to scan the nipple area with the laser. Worked on testing the network analyser which includes connecting it to the router, connecting to it from the Raspberry Pi, getting data from it and visualising the data. Have also helped integrate all the parts of the system into a main file which runs the system in the terminal. Have also set up a separate branch in Git dedicated to testing the complete system before merging everything to Master.

C. Märta Krönström

Have been working on simulations, testing and have been the main responsible for collision avoidance for the robot arm. Have implemented all the mentioned simulations and code for collision avoidance. Also, responsible for team-leader tasks.

D. Dennis Landré

Have been designing and 3D-printing a new robot end effector and new breast phantoms. Also been involved in programming calibration methods and accuracy testing of the robot. I have been part of the final assembly process of the product which includes mounting and finalising the central control box and the transmitter platform as well as integration testing them.

E. Filip Lindhe

Have been working on the surface reconstruction, comparing the two algorithms, and writing error metric functions to help make a decision on which of the algorithms should be used. Has also developed an algorithm to help choose points in 3d where the microwave antenna can be placed. Has also worked on writing functions to help visualize in 3d where the errors are located. Made one of the calibration scripts which is used to calibrate the work object's plane.

F. Jiantao Shen

Have been working on the GUI. Updating the design of the GUI and modifying the completed functionality to connect them to the GUI.

G. Samuel Wågbrant

Have been working with the robot arm. This includes ensuring that the robot arm does not reach its minimum or maximum limit on any of its joints which would entail that the robot arm aborts its execution, and finding optimal work object parameters (center point coordinates and angles in quaternions). Also, I started working on system integration by integrating system functionality into a complete system.

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Appendix A
Progress report 1

Progress Report 1 can be viewed on the following pages.

Progress Report 1-µTomography

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I. Project Information

Project title	**Client Sponsors**	**Project Team Leaders**	**Project Date**
Microwave Imaging for Breast Cancer Detection: A Non-Contacting Approach	Nikola Petrovic and Cristoph Salomon	**Software**: Märta Krönström **Hardware**: Dennis Landré	2023-10-30

Name	**Title**	**Responsibilities**
Dennis Landré	Hardware Team Leader	Ensuring the project meets hardware requirements. 3D Modeling.
Ihsan Haidari	Hardware Developer	Responsible for the platform and sender platform.
Märta Krönström	Software Team Leader	Ensuring the project meets software requirements. Responsible for simulations.
Joel Josefsson	Software Developer	Responsible for the Laser and distance measurements. 3D scanning patterns and Git.
Filip Lindhe	Software Developer	Responsible for the surface reconstruction
Jiantao Shen	Software Developer	Responsible for the GUI
Samuel Wågbrant	Software Developer	Responsible for YuMi and control systems.

II. Short project progress summary

This project is on track and so far, no substantial obstacles have been encountered. There are only a few delayed work packages and more information about which ones can be found in Section III and their recovery plan in Section VI. In relation to the planned scope, the team has almost completed the subgoal of automating measurements for an object with known symmetric geometry. The last big part of that component will be to include measurements with the microwave sensors.

The next steps for the software team are to continue optimizing the laser measurements, integrate all the functionality on the central control unit and GUI, and start working with the microwave measurements. For the hardware team, it is to place all the equipment and manage the cables for the central control unit and platform.

For more information about the status of each work package, see Section II and details about them in Section III.

There is also a plan to perform some tests in regard to controlling the calibration of the robot arm as a potential risk is that it is not accurate. For more specifics about this look at section VII.

III. Work Package Status

Table I
This table outlines the status of each work package together with the date when each package should be completed.

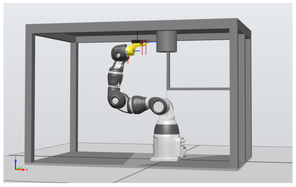
ID	**Work package**	**Deadline**	**Planning Status**	**Completion Status**
1.1.1	Robot arm	17/9-23	On track	In Progress
1.1.2	Platform	17/9-23	Off track	In Progress
1.1.3	Sender platform	31/10-23	On track	Completed
1.1.4	Robot tool/end-effector	1/10-23	Off track	In Progress
1.1.5	Breast phantoms	1/10-23	On track	In Progress
1.1.6	Central control system	15/10-23	Off track	In Progress
1.1.7	Network	22/10-23	On track	Completed
1.1.8	GUI	5/11-23	On track	In Progress
1.2.1	Laser	3/12-23	On track	Completed
1.2.2	Microwave measurements	3/12-23	On track	In Progress
1.2.3	Surface reconstruction	14/12-23	On track	In Progress

A. Robot arm - 1.1.1

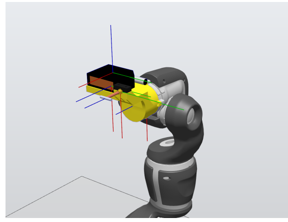
The ABB Single-Arm YuMi® IRB 14050 [1] is used for the initial scan of the breast phantom and to move the microwave antenna to the desired location during the microwave measurements.

1) Simulations: A standard test station has been created for the simulations, including obstacles such as the platform for the robot arm, the sender platform, and the breast phantom 1(a). An end-effector has been defined using a CAD model of the new tool. Three Tool Center Points (TCPs) have been defined; one for the antenna, one for the laser, and one used for calibration 1(b). The data for these TCPs can then be used to decide which tool to use. Further, collision sets have been created to be able to visualize any collisions. This can hence be used for controlling and testing the planned paths.

2) Communication: Communication between the Raspberry Pi and the YuMi is handled via a Transmission Control Protocol (TCP) socket connection where the YuMi will act as a socket server waiting for incoming commands from



(a) Simulation station



(b) End-effector

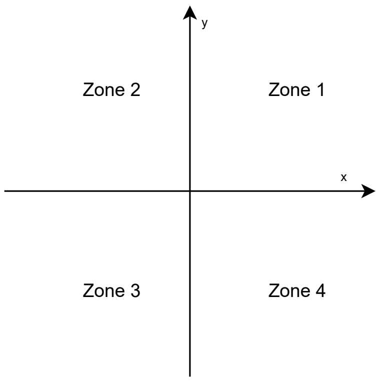


Figure 1. The logical zones created to plan the path of the robot. The zones are created to force the robot to travel sequentially through the zones to avoid collisions with the environment and to adjust the angle of the robot arm to optimize it to the current zone.

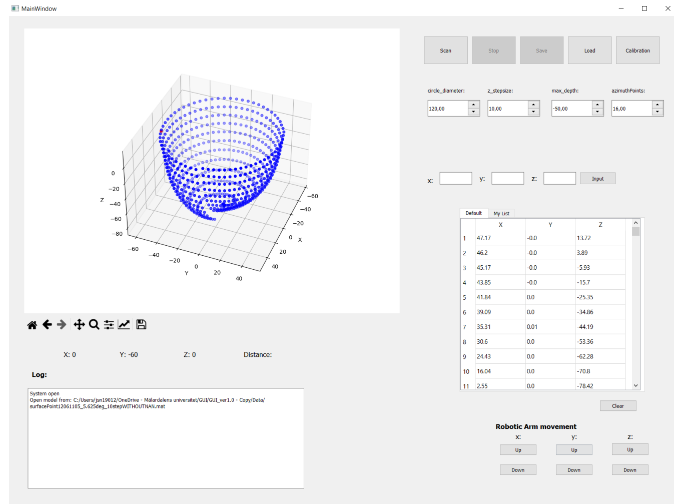


Figure 2. The figure shows the current UI design. Users can scan objects, save and load scan data simply by pressing the corresponding buttons. The system will automatically create a scan list based on circle_radius, z_stepsize, max_depth and azimuthPoints. Additionally, the scan results will be plotted on a chart and displayed in a table. Users can also create their own scan lists. Furthermore, users are able to move YuMi manually using GUI.

the Raspberry Pi. This is done via a Python program on the Raspberry Pi and an ABB Rapid program on the YuMi.

3) Path planning: A cylindrical pattern has been created as a path for the laser measurements where the z-axis of the laser always points inwards to the (0, 0) point in the plane. Another option has been made where the laser points upwards at a specific angle but always pointing inwards. Four different zones have been logically created to position the YuMi in a desired location when travelling to a position so as not to hit any equipment, see Figure 1. When travelling to a position that is placed in a different zone relative to the current zone, the YuMi will be forced to sequentially travel through zones to reach its new target position. The YuMi has been restricted from travelling directly from Zone 1 to Zone 4 to avoid reaching its joint limits. Continuing forward, the positioning of the joints needs to be refined in such a way that cables and equipment connected to the YuMi are not damaged or tangled when the YuMi is moved from one position to another.

4) Testing: The robot arm has successfully been tested both outside and inside of the new frame. Before each run, the paths have been simulated and confirmed to not collide with the environment. This testing will continue for both laser measurements and microwave measurements.

5) Next step: The next step for the robot arm is to develop a pattern for the microwave measurements. Also, to keep on testing with the laser.

B. Graphical User Interface

A Graphical User Interface (GUI) has been created, which includes functionality that meets the basic requirements of the project, such as scanning, saving, and reading scanned data in files, and displaying plots of scanned data. Figure 2 shows the design of the GUI, but it will be modified when more features are completed. Figure 3 shows the operation process of different buttons and what features have been completed so far.

The idea of the GUI is that when you press the scan button, the system will automatically connect YuMi and the laser and perform scanning. The scanning is based on *circle_radius*, *z_stepsize*, *max_depth* and *azimuthPoints* values. Once the scanning is completed, the scanning points will be plotted on the chart and values will be displayed on the "*default*" table. The 3D reconstruction will be displayed in a new window. You can stop the scanning by pressing the "*stop*" button. You can also save and load the data in a file. Furthermore, you can create your own scan list by inputting x, y, and z values on the "*mylist*" table. You can also move the laser to a specific point and point it at the model's surface. The calibration button is used to calibrate the origin of the system.

1) Next step: The plan for the GUI is to complete all the functions in Figure 3 and test them in Raspberry Pi. Once the GUI is working properly, more advanced features such as changing the laser angle will be implemented.

C. Platform

The platform is constructed using Medium-Density Fibreboard (MDF) and aluminium profiles as shown in Figure 4. A hole has been carved out on the top level of the plat-

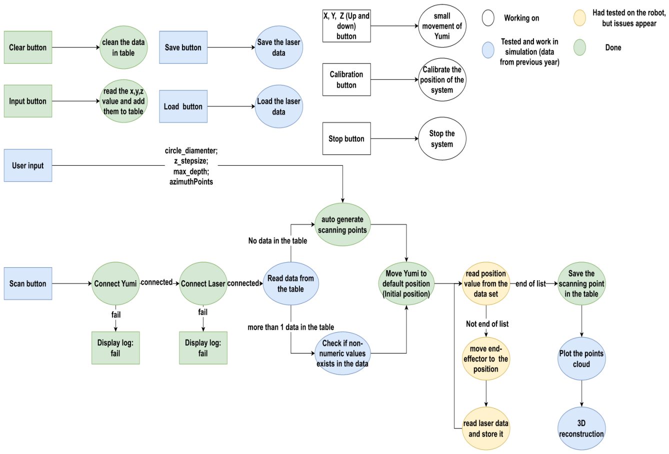


Figure 3. This diagram shows what features have been completed so far.

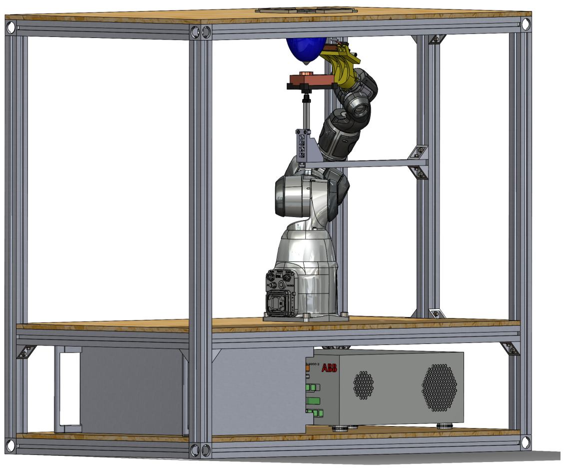


Figure 4. Platform

form and it is centred to accommodate the robot arm for suspending the breast phantom.

Modifications have been made to the initial design, including changing the sender platform. The previous sender platform was mounted to the lower surface under the breast phantom, preventing the robot arm from reaching around the breast phantom. The updated design, which is affixed to the side of the platform makes it possible for the robot arm to reach around the breast phantom, and also it offers increased stability, reduced noise level, and smaller step size. The next steps for this work package are placing all the equipment on the platform and cable management.

D. Sender platform

The sender platform comprises a microwave transmitter, a linear actuator [2], a stepper motor driver [3], and a step-down module [4]. The transmitter is mounted on the top of the linear actuator, allowing it to move in a range of 100 mm depending on the dimensions of the phantom. The step-down module is used to reduce the voltage from 20V to 3.3V, serving as the power source for controlling the linear actuator signals. An external power source is preferred over Raspberry Pi's power source due to its efficiency and it poses no damage to Raspberry Pi. The linear actuator has a step size of 0.01 mm, fulfilling its intended purpose by positioning the transmitter at a desired distance from the phantom. As of now, it is equipped with four functions: Ascending to a specified distance, descending to the zero position, ascending or descending by 1 mm. The functions are not final and they can be modified if it is needed. The next step is to integrate the functions into the GUI and test the performance of the sender system.

Figure 5. End-effectors with laser distance sensor and applicator mounted. The current version (black) has the applicator mounted below the laser sensor and the new version (yellow) has the applicator mounted next to the laser sensor.

E. Robot tool/end-effector

Figure 5 shows the current and the new design of the end-effector. The initial design was reworked as the applicator could not reach the upper parts (the base) of the phantom, at a right angle, as the laser sensor interfered with the ceiling of the platform. By keeping them at the same height, the laser and the applicator should have the same reachability. The next step in this work package is to 3D-print the tool and mount the sensor and applicator.

F. Breast phantoms

Symmetrical breast phantoms have been 3D-printed, in two different variants with different dimensions. The next step for this work package is to 3D-print asymmetrical phantoms based on some dimensions and images obtained from the stakeholders.

G. Central control system

Evaluation of the old control units (Arduino and Beagle Board) has been made and it was decided that it was best to change for increased performance. A new control unit in the form of a Raspberry Pi 4B [5] has been obtained. The team has started setting up everything on the Raspberry Pi, such as git, downloading necessary packages, creating a shell for all the functionality, etc. A control system box has been designed to house the Raspberry Pi, power supplies, motor controller, laser sensor cable adapter, and custom circuit boards. The next step for this work package is the cable management for the sensors, actuators, and robot arm.

Table II
TABLE SHOWING THE RESULT OF THE MANUAL TESTING OF THE OPTONCDT 1402

True distance (mm)	Measured distance (mm)	Error (mm)
150	150.87	0.87
140	140.77	0.77
130	130.42	0.42
120	120.97	0.97
110	110.60	0.60
100	100.30	0.30
90	90.37	0.37
80	80.42	0.42
70	70.18	0.18
60	60.42	0.42
50	50.24	0.24

H. Network

All devices, excluding the laser, communicate with each other via Ethernet. For this reason, a Local Area Network (LAN) has been created to enable communication between all devices. Devices that are stationary to the system are allocated static IP addresses within the network.

I. Laser

The Distance measurement sensor used is the optoNCDT 1402-100 [6]. The measured data arrives via a serial port to the connected computer. Each measurement consists of two consecutive bytes of 8 bits each. One has 1 as the biggest bit and the other 0. These two are combined into one 14-bit number and the distance from the sensor can be determined by equation 1

$$distance(mm) = 50 + \left(d_o * \frac{1.02}{16368} - 0.01\right) * 100 \qquad (1)$$

where d_o is the combined bits.

Code has been implemented to connect via serial to the sensor, to measure and calculate the distance, to set the internal measurement mode to moving average, and to turn the laser off and on via the serial port. However, turning the laser on and off by writing via serial proved to be unreliable as the message did not always get received. A solution has been made to include a transistor circuit to turn the laser on and off between measurements. For extra safety, a physical switch is put in series with the transistor circuit which decides the absolute state of the laser.

The data from the laser is then transformed to the point of the end-effector for all points which creates a point cloud of the scanned breast.

The laser have been tested by measuring distances from 50 mm to 150 mm in intervals of 10 mm using a ruler on a straight piece of wood. Another solid piece of wood was prompted up against the end where the 0mm line is. The optoNCDT 1402 was manually placed on each line and a measurement was taken. The result of the testing can be seen in Table II.

Six different test measurements were conducted one after the other to test the repeatability of the current robot/laser setup. The robot was set up to take measurements on 4 points on each of the 8 azimuth angles. The data was gathered and the five last measurements were each compared to the first measurement. The variance and difference between each measurement were calculated and can be seen in Table III and Table IV.

Table III
TABLE SHOWING VARIANCE IN THE DIFFERENCE BETWEEN EACH MEASUREMENT WHEN COMPARED TO THE FIRST MEASUREMENT.

Measurement	Variance in X(mm^2)	Variance in Y(mm^2)	Variance in Z(mm^2)
1	0.003	0.0006	0
2	0.002	0.001	0
3	0.002	0.001	0
4	0.003	0.001	0
5	0.003	0.001	0

Table IV
TABLE SHOWING MIN AND MAX VALUE IN THE DIFFERENCE BETWEEN EACH MEASUREMENT WHEN COMPARED TO THE FIRST MEASUREMENT.

Measurement	Min/Max difference in X(mm)	Min/Max difference in Y(mm)	Min/Max difference in Z(mm)
1	0/0.32	0/0.12	0/0
2	0/0.16	0/0.16	0/0
3	0/0.19	0/0.18	0/0
4	0/0.25	0/0.17	0/0
5	0/0.22	0/0.19	0/0

1) Next step: This package can be seen as done but some more testing could be done, specifically test how good the measurement is at an angle, if the time and resources allow for it.

J. Microwave measurements

The network analyser has been obtained, and the group has started getting familiar with it as well as testing communication, etc. The next step for this work package is to obtain the sensors (receiver and transmitter) and test using them. Also, to get a more thorough introduction from the supervisors.

K. Surface reconstruction

Four different surface reconstruction algorithms have been implemented and tested on the previous year's measured data. The four algorithms are : Alpha shape [7], Ball-pivoting algorithm [8], Cocone [9] and Poisson surface reconstruction [10]. Based on some simple tests using the aforementioned data it is concluded that cocone or poisson surface reconstruction algorithms will be used since Alpha shape and ball-pivoting algorithm did not produce watertight meshes.

Cocone works by performing a Delaunay tetrahedralization of an input point cloud, where the Delaunay tetrahedralization partitions the point cloud into non-overlapping tetrahedra, while ensuring that no input point lies within the circumsphere of any other tetrahedron. The algorithm then classifies all the tetrahedra as either inside point, outside point or surface tetrahedra, where the surface

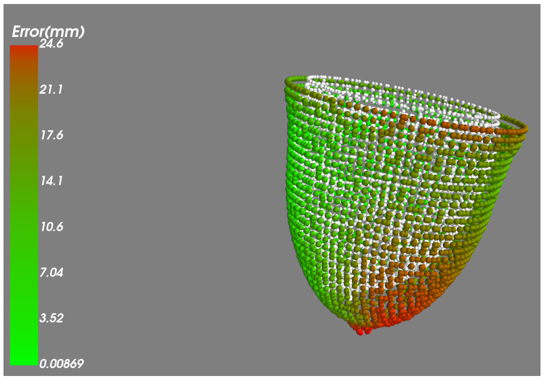


Figure 6. Showing each starting point of the raytracing as coloured dots, where the colour indicates the error in the distance and the white dots is the point cloud created from the reconstructed mesh.

tetrahedra is the classification that is relevant for the surface reconstruction. For each of the surface tetrahedra, the algorithm constructs a hierarchical structure that describes the local surface geometry, this hierarchical structure is called a "Cone-Tree". The algorithm then traverses all Cone-trees and connects the surface tetrahedras to form a continuous mesh.

The Poisson surface reconstruction works by first estimating the normal vectors at each point in the point cloud. After this, a 3D grid is placed over the entire space containing the point cloud, and each voxel in the grid is associated with a scalar value which is initially set to 0. The algorithm then sets up a Poisson equation for the scalar values of the voxels. The equation involves Laplace's equation which describes how the scalar value at each voxel relates to the values of its neighbours. The Poisson equation is weighted based on the estimated normal vectors as seen in equation 2

$$\nabla^2 \phi = -\nabla(n) \tag{2}$$

where ∇^2 is the laplacian operator, ϕ is the unknown surface, ∇ is the gradient operator and n is the estimated normal vector. When the Poisson equation is found the algorithm solves said equation, then uses an isosurface extraction technique to extract the surface. To implement Poisson surface reconstruction, a Python library called Open3d [11] was used.

An error estimation algorithm has been implemented using a raycasting method where it is possible to measure the distance from a point to the reconstructed mesh and thus measure how the reconstructed mesh differs from the CAD model used to create the known geometrical breast phantom.

1) Next step: When additional data have been collected further testing will be made to see which of the two algorithms produces the best results. Based on the results of these tests a decision will be made on which of the algorithms will be used in the final product.

IV. Completed Activities and Upcoming Activities

The following section details the completed activities and upcoming activities found in the project plan, see Appendix **??**.

A. Completed

The following list is based on the Work Breakdown Structure (WBS) and contains all the completed deliverables, work packages, and tasks. This means that if a work package is stated then all of the deliverables and tasks within it are completed (hierarchical order).

- 1.1.1.1 Deliverable Control of the robot arm
- 1.1.1.2.1 Task Test outside of frame
- 1.1.2.1.1 Task Mount all the boards and aluminium profile
- 1.1.2.1.2 Task Adding features for robustness
- 1.1.2.1.3 Task Safety features
- 1.1.2.1.6 Task Hole for breast phantom
- 1.1.3 Work package Sender platform
- 1.1.4.1.1 Task Evaluation and comparison of last iterations tool
- 1.1.4.1.2 Task Fit laser and antenna
- 1.1.4.1.3 Task Designing
- 1.1.4.1.6 Task Get dimensions of the microwave antenna
- 1.1.4.1.7 Task Print antenna for testing
- 1.1.5.2.1 Task Get the required dimensions
- 1.1.5.3 Deliverable Holder for phantoms
- 1.1.6.1.1 Task Evaluation of Beagle Board vs. Raspberry Pi
- 1.1.6.1.2 Task Possibly transition to Raspberry Pi
- 1.1.7 Work package Network
- 1.1.8.1.4 Task Buttons for control of laser measurements
- 1.1.8.1.5 Task Buttons for control of the microwave measurements
- 1.1.8.1.6 Task Visualisation of the measurements
- 1.2.1 Work package Laser
- 1.2.2.1 Deliverable Get familiar with the equipment
- 1.2.2.1.1 Task Obtain the equipment
- 1.2.2.1.2 Task Get introduction from supervisors
- 1.2.3.1 Deliverable Implement algorithms

B. Upcoming

The following list is also based on the WBS and includes the upcoming activities within the project.

- 1.1.1.2.2 Task Test inside of the frame
- 1.1.1.3 Deliverable Documentation
- 1.1.2.1.4 Task Equipment placement
- 1.1.2.1.5 Task Cable management
- 1.1.2.4 Deliverable Documentation
- 1.1.4.1.4 Task 3D-Printing
- 1.1.4.1.5 Task Mounting
- 1.1.4.2 Deliverable Documentation
- 1.1.5.1 Deliverable Old phantoms
- 1.1.5.2.2 Task 3D-print prototypes

- 1.1.5.3 Deliverable Documentation
- 1.1.6.2 Deliverable Connection management
- 1.1.8.1.1 Task Emergency stop button
- 1.1.8.1.2 Task Buttons for control of robot arm in different coordinate systems
- 1.1.8.1.3 Task Buttons for control of sender platform
- 1.1.8.1.7 Task Visualisation of results
- 1.1.8.1.8 Task Controls with manual control similar to the joystick on the controller
- 1.1.8.2 Deliverable Documentation
- 1.2.2.2 Deliverable Functionality for the measurements
- 1.2.2.2.1 Task User can choose area
- 1.2.2.2.2 Task Scanning points based on given positions
- 1.2.2.2.3 Task Move transmitter and receiver to defined positions
- 1.2.2.2.4 Task Perform measurements
- 1.2.2.2.5 Task Save data
- 1.2.2.3 Deliverable Documentation
- 1.2.3.2 Deliverable Evaluate algorithms
- 1.2.3.3 Deliverable Documentation

V. Accountability for Off-Track Work Packages

The responsible for the work packages 1.1.2, 1.1.4, 1.1.5, and 1.1.6 is the hardware team.

VI. Recovery Plan for Off-Track Work Packages

A lot of the work packages are in fact ahead of their planned timelines and can therefore compensate for some of the ones falling behind.

A. 1.1.2 Platform

For the platform what is left is placing all the equipment on the platform and cable management. For this, resources will be reallocated to fix it.

B. 1.1.4 Robot tool/end-effector

A second iteration of the Robot tool is under development and will be completed during week 43.

C. 1.1.5 Breast phantoms

The asymmetrical phantom should be printed. There is no current need for it and therefore more time can be allocated to finish it.

D. 1.1.6 Central Control System

For the control system, cable management is what remains. This package is a priority and hence, resources will be reallocated to fix this.

VII. Issues, Blockers and Risk Status

A potential risk could be the current calibration of the robot arm. The team had to re-calibrate it by updating the revolution counters [12] and this could have affected the precision of it. The steps for calibration were followed, meaning that all the axes marks were set into place and then the counters were updated. When testing there has been some offset from the expected results and this might be because of the calibration.

The first step to control if this is an actual risk was to test the accuracy and precision of the robot arm by using the laser. This showed that the repeatability was good. The accuracy was a bit off and this is something that could be compensated by the software, but ideally, the robot arm would need to be checked. The group is working on getting in contact with someone on ABB who could possibly control if the calibration is accurate. Even if the measurements indicate that the precision is correct it could be good to get it checked.

VIII. Individual Contributions

A. Ihsan Haidari

Have been working on the sender platform including the step-down module, the code for the linear actuator, the design of the system, and the testing. Also partially working on the platform including construction of the platform and cooperating with the designing and printing of the 3D parts.

B. Joel Josefsson

Have been working on the laser, making the code for operating the laser and the transformation from distance to point cloud, setting it up and testing it. Made code for the path planning of the end-effector on the robot. Have started to look into the network analyser.

C. Märta Krönström

Have been working with the robot arm. Simulations and testing. Have also been responsible for team-leader work such as preparing material for meetings, planning, dividing tasks, documentation, and contact with stakeholders.

D. Dennis Landré

Have been designing the sender platform, electronics control box, end-effector tool, complete electronic circuit schematic, step down circuit, digital laser off switch circuit, breast phantoms, platform and calibration tool which have been 3D-printed, soldered or constructed. I have also ordered the necessary parts needed.

E. Filip Lindhe

Have been working mainly on the surface reconstruction work package, This includes researching viable surface reconstruction algorithms, implementing algorithms, and implementing an error metric algorithm which can be used to test the surface reconstruction algorithm.

F. Jiantao Shen

Have been working on the GUI side, creating the design of the GUI and connecting the completed functionality to the GUI.

G. Samuel Wågbrant

Have been working with the robot arm. This includes the communication between the robot arm and the connecting control system, ensuring the robot arm follows the determined path in a safe manner, and creating an interface to control the robot from the control system.

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APPENDIX B
PROJECT PLAN

The original project plan can be viewed on the following pages.

Project plan

Project title	Client / Sponsor	Project team leaders
Microwave Imaging for Breast Cancer Detection: A Non-Contacting Approach	Nikola Petrovic and Cristoph Salomon	Software: Märta Krönström Hardware: Dennis Landré

1 Executive summary

The research field for this project is Microwave Imaging (MWI) for breast cancer detection. In MWI, non-ionizing microwaves penetrate the surface, scatter throughout the object and reflect back to a receiver. An image can then be reconstructed based on the dielectric properties of the object. Since breast tumours have different dielectrics than healthy breast tissue, the image will show if any tumours are present in the breast.

This project is performed in close collaboration with the Biomedical Engineering Research group at Mälardalen University (MDU) [1]. During their research, they developed a sensor for MWI applications, specifically breast cancer detection, which uses electromagnetic waves in an efficient matter to irradiate the breast. To obtain the signal from this sensor, a receiver antenna must be employed, which should be moved closely around the object to measure the transmitted signal strength at different positions. For this purpose, the researchers acquired an ABB Single-Arm YuMi (SAY) collaborative robot where the end-effector is meant to contain the receiver [2].

The goal of this project is to be able to perform a series of automated microwave measurements using the previously mentioned equipment. The object to measure is a breast phantom and the goal can further be divided into two parts. The first part is to be able to measure a breast phantom with known geometry, and the next is to measure one with unknown geometry. The purpose of this project is to contribute to the ongoing research efforts of the project's stakeholders. Specifically, to develop a non-contacting, non-ionizing breast cancer scanning system utilising MWI technology.

The main tasks of the project will be to set up the robot arm along with the other hardware provided. Furthermore, a Graphical User Interface (GUI) needs to be developed to move the microwave transmitter and receiver to defined positions around the breast phantom with known geometry. Moreover, laser-based surface estimation should be used to perform automated measurements on a breast phantom with unknown geometry.

2 Background

Breast cancer is the most common form of cancer in women. Statistics from the International Agency for Research on Cancer state that in 2020 around 25% of all new cases of cancer in women were breast cancer with 2 261 419 new cases and 684 996 deaths worldwide [3, 4]. World Health Organization also projects increases in new cases of breast cancer by up to 91.2% and death by up to 94.2% in 2020-2040 [5]. Early stages of breast cancer often appear as lumps in the breast with little to no other symptoms. These cancerous lumps can then spread cancer to the lymph nodes if left untreated. However, if caught before they spread, the tumours can be treated more successfully [6]. Thus, making the need for early detection prominent. The main screening method for detecting early breast cancer today is mammography where the naked breast is squeezed between two plastic plates and then X-rayed. This procedure can be both uncomfortable and sometimes painful [7]. Studies have shown that the main reason for not getting a re-screening when invited is that it was painful to do the first one [8, 9]. The ionizing radiation from the X-ray could also induce breast cancer in the patient which would cause more harm than benefit [10]. Clearly, a more comfortable, painless, and safe method must be developed.

One promising method to differentiate between healthy breast tissue and tumours in the breast is Microwave Imaging (MWI) [11]. The technique of MWI uses non-ionizing electromagnetic microwaves to develop internal images of the breast based on the electric properties of the breast tissue and the tumour. The microwaves penetrate through the breast, scatter, and reflect. These scattered, reflected signals are received and an internal image of the breast is constructed. Since the dielectric properties of malignant breast tissue differ from healthy breast tissue, the image will show if there are tumours present.

Commonly in MWI, an array of antennas is used around the breast to illuminate it with microwaves [12, 13, 14, 15, 16]. There are a few different methods to acquire signals from the setup. One popular method is Confocal Microwave Imaging (CMWI) [14, 15, 16]. This method is radar-based which only considers the reflected backscattering from the object using one antenna at a time. Another method is Microwave Tomography (MWT) [12]. This method considers only the scattered signals transmitted from the object. These two methods also produce different images. CMWI is a more simple approach that attempts to identify the position of significant scattering in the breast. This can be done with beamforming algorithms such as Delay-Multiply-and-Sum [16]. MWT is a more complex method as it aims to use an inverse scattering method to get the diagnostic image of the breast. This method is calculation-heavy and requires image reconstruction algorithms to generate a map of permittivity and conductivity [11]. One popular way to get this is the Gauss-Newton method [17].

Since the difference in electrical properties between the air and the skin is so high the signals reflect early. These early-reflected signals can be quite large and can hide the reflected signals of the tumours. To mitigate these effects, researchers put the breast and the antenna array in a coupling medium. This is often a liquid with the same electrical properties as the tissue [12, 18, 19]. However, recently some researchers have developed a way to do MWI in a dry setup by mitigating the early skin reflection using Singular Value Decomposition (SVD) [20].

The research on MWI using breast phantoms at Mälardalen University (MDU) started in 2014 [21]. A receiving antenna was mounted on a robotic arm with six degrees of freedom. One identical antenna was mounted on the fixture which was placed in a pool filled with water as a propagating medium. A stepper motor was also mounted on the fixture that spins the object of interest to get imaging from different angles. The robotic arm with the receiving antenna was able to scan the object in a half-spherical, cylindrical, or planar manner around the object. The phantom used was a cylinder made from polycarbonate filled with deionized water and Troton X-100. Another, smaller cylinder of the same material but with salt added in the fluids was put inside the larger one to simulate a tumour.

In 2017, researchers at MDU theorised a new system designed to work in the open air instead of in a coupling liquid. They concluded that problems with surface waves can be avoided by using excitation devices [22]. They later designed a novel microwave applicator that is used without coupling liquids. This is done by designing the applicator to not couple energy into the air but directly into the breast [23]. In 2022 students at MDU worked on a system to be used with the applicator and an antenna. They used a Single-Arm YuMi (SAY) and a laser distance sensor to make a 3D model of a 3D-printed breast phantom. They also made a 3D-printed, motor-controlled moving platform for the microwave applicator to be positioned under the breast [24].

Collaborative robots or cobots are robots that collaborate with humans. These robots have successfully been implemented in several different industry settings [25]. Recently, they have also been implemented as a tool in the medical field to assist personnel with different tasks. Robot-assisted surgery is one field in which robots are used to assist the surgeon in performing minimally invasive surgery on patients [26, 27, 28].

ABB Robotics is well known for its wide variety of robots in various sizes and reach. One collaborative robot by ABB is the Single-Arm YuMi® IRB 14050, a one-armed descendant of the Dual-Arm YuMi introduced in 2015. It is designed with seven axes whose movements mimic that of a human arm. The robot is lightweight and has a small footprint making the position in which can be mounted flexible. The SAY is specifically made to work alongside humans, thus having the option of safety features such as ABB's Safemode [2].

Surface reconstruction refers to the method of generating a soft copy of the data of an object given scanned data of the object [29]. The scanned data can be arranged in a few ways. One way is by having the input data as a point cloud, a set of structured or unstructured points. In a 3D representation, the points can be the x, y, and z coordinates of the data. Most likely, the data from scanning an object is unstructured where no connectivity is received. This makes this sort of data computationally heavy and hard to reconstruct.

Over the years, quite a few algorithms for surface reconstruction have been developed using different methods. One popular method is to make triangulated surfaces using Voronoi diagrams and Delaunay triangulation. A Voronoi diagram of a plane divides the plane into polygonal regions where every point has its region. The size of every region is all points in the plane that are closer to the associated point than any other point [30]. Delaunay triangulation constructs triangles from points in the plane in which the triangles are as equiangular as possible using circumcircles [31].

The α-shape algorithm [32, 33] uses Voronoi diagrams and Delaunay triangulation to construct a family of α-shapes to get the shape of an object. The Crust algorithm [34] uses both Voronoi diagrams and Delaunay triangulation but also the medial axis to reconstruct the surface. Power Crust [35] is an improved version of the Crust algorithm, however, when the sampling is too dense the time it takes to run the algorithm is very high [30]. Another algorithm is Cocone [36] which is a simplification of the Crust algorithm. The Tight Cocone [37] is a watertight version of the Cocone algorithm which fills up the holes left behind from another surface reconstruction algorithm.

This project aims to perform MWI on breast phantoms of both known and unknown geometry using the provided microwave applicator and antenna with feedback to the user. To achieve this, the breast phantom will be scanned from several angles using a SAY equipped with a laser distance sensor and reconstructed in 3D. A Graphical User Interface

(GUI) will be developed to provide feedback and control. The microwave applicator will be positioned accurately below the phantom and the antenna will be positioned using the same SAY.

2.1 State Of the Art

As mentioned in the previous section, MDU researchers proposed a groundbreaking system designed for operation in the open air, eliminating the need for coupling liquids. They determined that employing excitation devices can avoid issues associated with surface waves [22]. They later designed another microwave applicator, which transmitted energy directly into the breast instead of air [23]. In 2022, MDU students worked on a project involving an applicator and an antenna. They employed a laser distance sensor and a SAY to reconstruct the surface of a breast phantom. The antenna was positioned on the Yumi arm alongside a laser-based distance sensor and a stepper motor-driven actuator to position and relocate the microwave applicator under the breast. The surface reconstruction accuracy in this project fell short of the desired level with a mean error of 17.5 mm, which made it difficult to evaluate the methods used [24].

In the research conducted by Kurrant *et al.* [38], they successfully generated breast surface estimates by employing various sensing modalities. The system used in this research consists of a microwave measurement tank filled with a coupling medium, a laser, an electromagnetic sensor attached to an arm, an adjustable antenna, and an external camera for the breast's position and antenna placement. The arm moves vertically within the microwave measurement tank at a specified distance from the breast phantom to capture its profile using laser samples. The surface model is built by creating evenly distributed contours along the object's height using data from estimated profiles. The separation between these contours is determined by calculating the difference in height, and the extent along the z-axis remains constant for all profiles. These calculations are then used to produce the object's surface by equilateral triangles. Three breast models were tested with the best result at 0.90 mm and the worst result at 1.18 mm of distance error mean, with 20 profiles which is the protocol at the University of Calgary. The process of scanning takes less than 30 minutes per breast depending on the amount of the profiles.

Pallone *et al.* [39], created an innovative laser scanning system with the ability to precisely reconstruct a surface representation of breast-shaped phantoms. This scanning system employs two laser line generators and a compact Charged-coupled device (CCD) camera is arranged concentrically on a rotating gantry positioned around the microwave imaging tank making it possible to rotate around the centre of the imaging tank where the breast phantom is positioned. This article outlines the design and functioning of the laser scanner and evaluates the effectiveness of several calibration methods such as analytical ray tracing and piecewise linear, locally weighted mean, polynomial, and thin-plate-spline image registration. In this research, the calibration through image registration consistently achieved mean surface errors of under 0.5 mm depending on the geometric complexity of the scanned object. In comparison to the ray tracing strategy, all the image registration methods performed better. However, the authors determined the global polynomial methods as the most effective in striking a balance between average surface error and scanner reliability. The laser scanning system offers a rapid and precise means of capturing 3D surfaces in the typical watery surroundings encountered during microwave breast imaging. Optical distortions caused by the imaging tank and coupling bath reduced the efficiency of the ray tracing method. Nevertheless, calibration using image registration techniques consistently generated scans with sub-millimetre precision.

In pursuit of rapid 3D surface reconstruction from scattered point clouds, Wang [40] introduces an innovative algorithm for laser imaging radar. This algorithm aims to reconstruct a detailed 3D depth surface using both depth and image data. The process begins with the division of 3D space into smaller units called voxels and outliers are then identified using point histogram features. Next, Gaussian process regression is applied to create a surface resembling a Gaussian distribution. Finally, they combined high-resolution grey data with 3D interpolation points, using Markov random fields for this purpose, where the result is a dense 3D depth surface. Experimental results confirm significant improvements in reconstruction accuracy and robustness. The proposed algorithm performs better compared to other algorithms such as Joint Bilateral Upsampling (JBU), Anisotropic Total General Variation (ATGV) and Markov Random Field model (MRF). While both the JBU and ATGV algorithms demonstrate good reconstruction capabilities, their complexity remains too large for practical engineering applications.

To improve Diffuse optical tomography, Morris *et al.* [41] developed a breast shape acquisition system in their research. This Structured Light Imaging system (SLI) which uses two cameras and a central projector, acquires accurate breast shape information in a way that is similar to mammography. The system adjusts the intensity of the lighting to accommodate different skin tones and minimizes issues caused by reflections. The SLI system is securely positioned on a stationary compression plate, in front of the patient's breast. The fundamental idea behind the SLI system is to obtain 3D surface information by analyzing multiple 2D images of predefined distorted patterns. The proposed SLI system was designed to offer a compact, cost-effective solution especially for the challenges posed by low-light conditions and the limited space requirements of mammography compression settings. The system achieves sub-millimeter resolution, with a mean surface error of 0.26 mm.

3 Purpose

The purpose of this project is to further advance the research of the project owners by designing a system that can perform a non-contacting and non-ionizing screening for breast cancer using MWI. Subsequently, the project will give the owners of the project a platform on which to advance the research even further.

4 Goal

The goal of the parent project is to design a system which can conduct automatic microwave measurements to detect breast cancer. This iteration of the project will focus on designing a prototype system which can make automated microwave measurements on a simple breast phantom first with known, then with unknown geometrics.

5 Scope

The scope of the project is described by a Work Breakdown Structure (WBS), see Section 9.1.

6 Limitations

To create realistic expectations among the different stakeholders, the project introduces the following limitations:

- The project is **constrained** to 19 weeks.
- The project is **limited** to a budget of 20 000 SEK.
- The project will **not** perform testing on human subjects.
- The finished product **lacks** safety certifications.
- The finished product **lacks** energy saving certifications.
- The finished product **lacks** EMI/EMC certificate.
- The team will **not** produce a product meant for commercial use and only create a proof of concept.
- The end product will **not** encompass an automated process.
- The surface reconstruction software will **not** produce an exact replica of the scanned object.
- The finished product will **not** be designed with patient practicality in mind.
- The SAY control programming language is **limited** to RAPID.
- The number of licenses for Robot Studio are **limited** and can only be used on the school computers.
- The software is **not** guaranteed to be free of bugs.
- Software to process microwaves will **not** be produced.

7 Requirements

The requirements for the product can be categorized into hardware and software requirements. All these are considered soft requirements, meaning that they are not absolute.

7.1 Hardware product requirements

The requirements for the hardware can further be divided into functional and non-functional requirements.

7.1.1 Functional requirements

The functional hardware requirements outline the specific hardware-related tasks and operations that the product is expected to perform.

- The microwave transmitter position **shall** be adjustable in height to accommodate different objects under study sizes.
- Laser distance measurement sensor **shall** only be active when stationary and distance measurement mode is active.
- The laser **shall** be able to turn OFF manually in a critical situation.
- The user frame origin of the SAY and the base centre of all objects under study **shall** coincide without needing realigning.

7.1.2 Non-functional requirements

The non-functional hardware requirements describe the hardware-related specifications of the product in detail.

- The SAY **shall** have pose repeatability within 1 mm.
- The microwave receiver of the SAY **shall** be able to reach all points on the surface from 10 degrees to 60 degrees in elevation angle of the object under study, perpendicular to the surface, without colliding with anything.
- The distance between the microwave transmitter and the object under study **shall** be 1 mm.

7.2 Software product requirements

The software requirements can also be divided into functional and non-functional requirements.

7.2.1 Functional requirements

The functional requirements for the software describe the functions that the product must do.

- The SAY **shall** avoid collisions with the environment.
- The SAY **shall** not damage the mounted microwave receiver and laser distance sensor.
- The 3D reconstruction algorithm **shall** digitally reconstruct the object under study with the provided scanning data.
- The movement of the SAY **shall** be synchronized with the microwave measurement equipment to perform automated measurements.
- The system **shall** be able to generate visual images from the laser data for the user.
- The user **shall** be able to control the robot arm manually.
- The SAY **shall** be able to move to a specific position given by the user.

7.2.2 Non-functional requirements

The non-functional requirements for the software relate to the technical specifications of the product in a detailed way.

- The SAY **shall** be controllable through software in all directions with a step size smaller than 1mm.
- The system **shall** be able to produce a point cloud consisting of 120 points in less than 10 minutes.

7.3 Project requirements

The requirements of the project can be specified as follows:

- The development phase of the project **shall** be finished on the 14th of December 2023.
- The project **shall** be finished on the 11th of January 2024.
- All documents, code, and equipment **shall** be stored and returned according to the specified handover plan, see Section 17.

7.4 Prerequisites

Prerequisites that need to be provided by the project owners are the SAY collaborative robot and the microwave imaging system, which includes the signal analyzer, antennas, cables and any relevant software.

8 Situational analysis and stakeholders

The following section gives an overview of the current situation by presenting a SWOT analysis. Additionally, the different stakeholders of the project are presented.

8.1 SWOT-analysis

The following SWOT analysis gives an overview of internal and external factors that can influence the execution and result of the project.

Strengths:

- Agile team which can adapt quickly to changes.
- Broad skill set among the team members, with backgrounds within both robotics- and network engineering.
- Stakeholders have a lot of knowledge of the subject.

Weaknesses:

- Limited funding.
- Lack of experience operating and controlling autonomous robots.
- Limited time frame.
- Limited knowledge of microwave imaging.

Opportunities:

- Collaboration with researchers.
- Be a part of creating a novel system.
- Testing new technology.
- Possibility to be part of publishing a paper if the measurements are successful.
- This project can continue as a master thesis.

Threats:

- Acquired equipment being defective upon arrival.
- ABB SAY robotic arm relies on technology from ABB. Meaning if something goes wrong with the robotic arm, the progress of the project may slow down.
- Equipment can be damaged or lost for some reason including burned or stolen. It slows down the progress of the project.

Conclusions:

- Need to ensure the quality and functionality of equipment early to quickly adapt and find other solutions.
- Be careful with how we store the equipment and lock away the items that could risk being stolen.
- Keep in contact with ABB so they can provide assistance if the equipment needs to be calibrated or fixed in some way.
- Planning is important to use the time in a good way.
- By collaborating with researchers and stakeholders, their expertise and resources can be used to overcome our limited knowledge of microwave imaging.

8.2 Stakeholder mapping

- **Internal Stakeholders:** Nikola Petrovic and Cristoph Salomon are the stakeholders in this project.
- **Investors:** ABB provided the SAY.
- **Partners:** Mälardalen University.
- **Customers:** Hospital employees will operate this product once it is fully developed.
- **Competitors:** Umbria Bioengineering Technologies have developed and patented Mammowave which uses microwaves for breast cancer detection [42]. Wavelia is another competitor that also uses microwaves for breast cancer detection [43].

9 Planning

This section contains the planning of the project, which includes a WBS and Gantt chart to visualise what needs to be done and when it should be finished.

9.1 Work breakdown structure

This section contains a WBS diagram for the whole project, including both software and hardware. The root of the WBS is the project itself. There are two main components that represent the broad stages of the project. Further, there are several work packages representing the breakdown of what has to be done to achieve each component. There are also deliverables, which are the tangible or intangible products or services that are developed during the project. Deliverables can therefore be handed over in digital or physical format. At the bottom of the WBS hierarchy are the tasks, which describe all the work necessary to complete each deliverable.

ID	Type	Activity
1	Root	Microwave Imaging for Breast Cancer Detection: A Non-Contacting Approach
1.1	Component	Perform automated microwave measurements on a simple breast phantom with known geometrics
1.1.1	Work package	Robot arm
1.1.1.1	Deliverable	Control of the robot arm
1.1.1.1.1	Task	Test range of motion manually
1.1.1.1.2	Task	Socket connection/communication
1.1.1.1.3	Task	Get familiar with Robot Studio
1.1.1.1.4	Task	Path planning
1.1.1.1.5	Task	Collision avoidance
1.1.1.1.6	Task	Transformation between coordinate systems
1.1.1.1.7	Task	Arm angle
1.1.1.1.8	Task	Simulations
1.1.1.1.9	Task	Save positions
1.1.1.1.10	Task	Move manually
1.1.1.1.11	Task	Calibration
1.1.1.2	Deliverable	Testing
1.1.1.2.1	Task	Test outside of frame
1.1.1.2.2	Task	Test inside of frame
1.1.1.3	Deliverable	Documentation
1.1.2	Work package	Platform
1.1.2.1	Deliverable	Set up the new frame
1.1.2.1.1	Task	Mount all the boards and aluminum profile

9.1 Work breakdown structure

ID	**Type**	**Activity**
1.1.2.1.2	Task	Adding features for robustness
1.1.2.1.3	Task	Safety features
1.1.2.1.4	Task	Equipment placement
1.1.2.1.5	Task	Cable management
1.1.2.1.6	Task	Hole for breast phantom
1.1.2.4	Deliverable	Documentation
1.1.3	Work package	Sender platform
1.1.3.1	Deliverable	New platform
1.1.3.1.1	Task	Evaluation and comparison of the old platform
1.1.3.1.2	Task	Designing
1.1.3.1.3	Task	3D-Printing
1.1.3.1.4	Task	Positioning
1.1.3.1.5	Task	Get dimensions of transmitter
1.1.3.1.6	Task	3D-Print transmitter for testing
1.1.3.2	Deliverable	Automated control
1.1.3.2.1	Task	Moving functionality
1.1.3.2.2	Task	Motor control
1.1.3.2.3	Task	Testing
1.1.3.3	Deliverable	Documentation
1.1.4	Work package	Robot tool/end-effector
1.1.4.1	Deliverable	New tool
1.1.4.1.1	Task	Evaluation and comparison of last iterations tool
1.1.4.1.2	Task	Fit laser and antenna
1.1.4.1.3	Task	Designing
1.1.4.1.4	Task	3D-Printing
1.1.4.1.5	Task	Mounting
1.1.4.1.6	Task	Get dimensions of the microwave antenna

ID	Type	Activity
1.1.4.1.7	Task	Print antenna for testing
1.1.4.2	Deliverable	Documentation
1.1.5	Work package	Breast phantoms
1.1.5.1	Deliverable	Old phantoms
1.1.5.1.1	Task	Obtain the available phantoms
1.1.5.2	Deliverable	New phantoms
1.1.5.2.1	Task	Get the required dimensions
1.1.5.2.2	Task	3D-print prototypes
1.1.5.2.3	Task	3D-print using printer in Eskilstuna
1.1.5.3	Deliverable	Holder for phantoms
1.1.5.3.1	Task	Design
1.1.5.3.2	Task	3D-printing
1.1.5.3	Deliverable	Documentation
1.1.6	Work package	Central control system
1.1.6.1	Deliverable	New control unit
1.1.6.1.1	Task	Evaluation of Beagle Board vs. Raspberry Pi
1.1.6.1.2	Task	Possibly transition to Raspberry Pi
1.1.6.2	Deliverable	Connection management
1.1.6.2.1	Task	Sensors and actuators
1.1.6.2.2	Task	Robot arm
1.1.6.3	Deliverable	Documentation
1.1.7	Work package	Network
1.1.7.1	Deliverable	Connection between all subsystems
1.1.7.1.1	Task	Robot controller and robot arm
1.1.7.1.2	Task	PC
1.1.7.2	Deliverable	Documentation

ID	Type	Activity
1.1.8	Work package	GUI
1.1.8.1	Deliverable	Interface for control and displaying results
1.1.8.1.1	Task	Emergency stop button
1.1.8.1.2	Task	Buttons for control of robot arm in different coordinate systems
1.1.8.1.3	Task	Buttons for control of sender platform
1.1.8.1.4	Task	Buttons for control of laser measurements
1.1.8.1.5	Task	Buttons for control of the microwave measurements
1.1.8.1.6	Task	Visualisation of the measurements
1.1.8.1.7	Task	Visualisation of results
1.1.8.1.8	Task	Controls with manual control similar to the joystick on the controller
1.1.8.2	Deliverable	Documentation
1.2	Component	Perform automated microwave measurements on a simple breast phantom with unknown geometrics
1.2.1	Work package	Laser
1.2.1.1	Deliverable	3D-Scanning
1.2.1.1.1	Task	Distance measurements
1.2.1.1.2	Task	Turn on/off
1.2.1.1.3	Task	Distance in mm
1.2.1.1.4	Task	Moving average
1.2.1.1.5	Task	Get general information from sensor
1.2.1.1.6	Task	Save sensor data
1.2.1.2	Deliverable	Safety features
1.2.1.2.1	Task	Physical emergency stop button
1.2.1.3	Deliverable	Testing
1.2.1.3.1	Task	Box/cover to make it dark for measurements
1.2.1.3.2	Task	Test range

9.1 Work breakdown structure

ID	Type	Activity
1.2.1.4	Deliverable	Calibration
1.2.1.4.1	Task	3D-Print calibration holder
1.2.1.5	Deliverable	Documentation
1.2.2	Work package	Microwave measurements
1.2.2.1	Deliverable	Get familiar with the equipment
1.2.2.1.1	Task	Obtain the equipment
1.2.2.1.2	Task	Get introduction from supervisors
1.2.2.2	Deliverable	Functionality for the measurements
1.2.2.2.1	Task	User can choose area
1.2.2.2.2	Task	Scanning points based on given positions
1.2.2.2.3	Task	Move transmitter and receiver to defined positions
1.2.2.2.4	Task	Perform measurements
1.2.2.2.5	Task	Save data
1.2.2.3	Deliverable	Documentation
1.2.3	Work package	Surface reconstruction
1.2.3.1	Deliverable	Implement algorithms
1.2.3.1.1	Task	Evaluation of the algorithms used during the last iteration
1.2.3.1.2	Task	Research algorithms
1.2.3.1.3	Task	Load saved model
1.2.3.1.4	Task	Save created model
1.2.3.1.5	Task	Display model
1.2.3.2	Deliverable	Evaluate algorithms
1.2.3.2.1	Task	Metrics for evaluation
1.2.3.2.2	Task	Visualisation of result
1.2.3.3	Deliverable	Documentation

9.2 Schedule

Following is a Gantt chart for the whole project, including both software and hardware. The schedule is based on the WBS, where the work packages and their deliverables have been scheduled. During the time frames for each work package the tasks will be scheduled using a Kanban board in Microsoft Teams Planner. This method is further explained in Section 12.1. This schedule is an estimation and it can change during the execution, many of the work packages will be started earlier and can be performed in parallel as long as the resources allow for it.

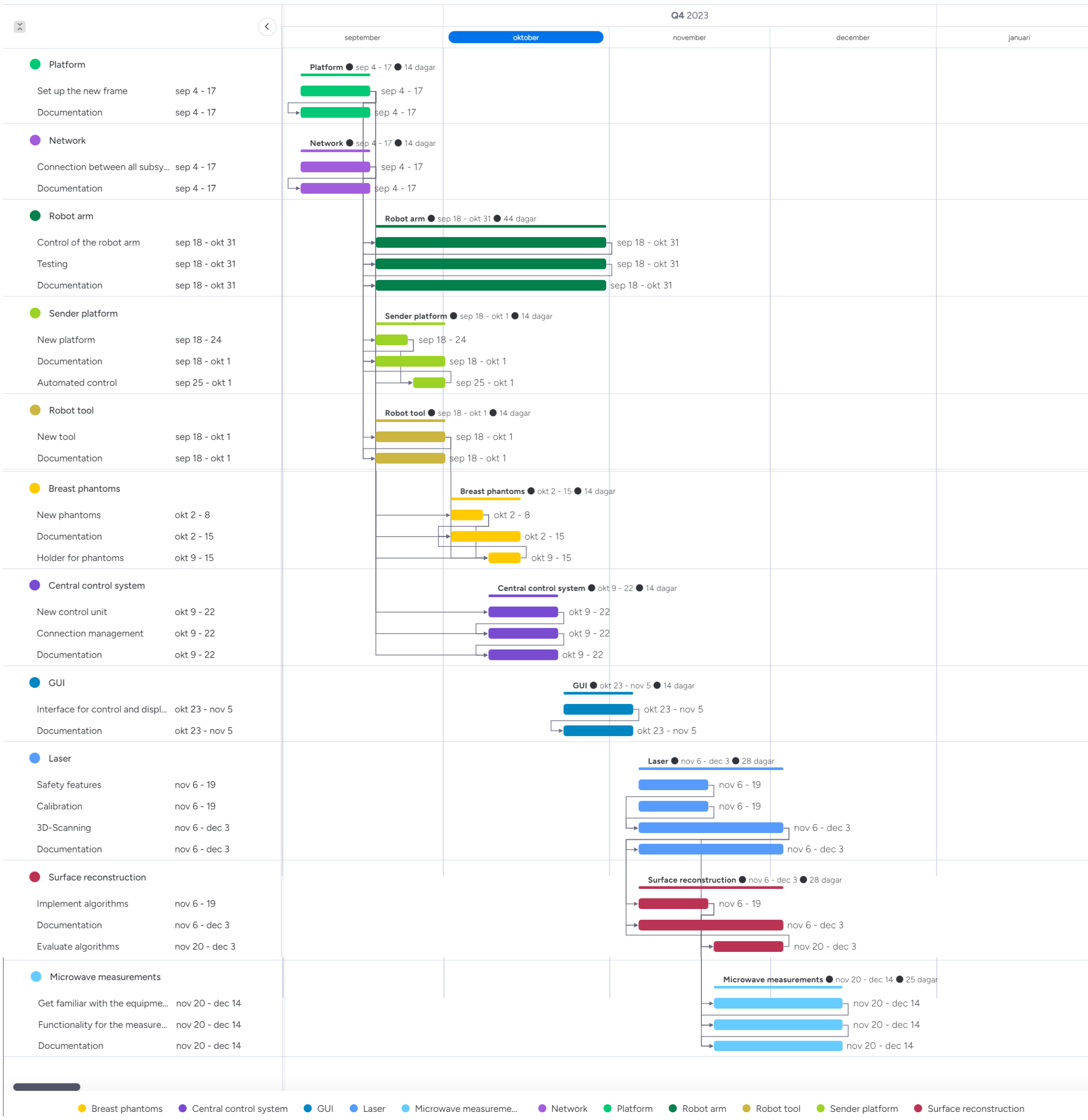

Figure 1: Gantt chart displaying an approximation of the timeline for the project.

10 Staffing

The staffing of the project outlines the responsibilities for each role as well as assigns a role to each member of the team.

10.1 Roles, responsibilities and authorities

- **Hardware Team Leader:** Oversees the hardware team, coordinates with the software team lead and is responsible for hardware-related tasks.

- **Hardware Developer:** Produces and designs hardware components, tests the hardware and deals with issues regarding the hardware.
- **Software Team Leader:** Oversees the software team, coordinates with the hardware team lead and is responsible for software-related tasks.
- **Software Developer:** Develops and tests software and deals with issues regarding the software.

10.2 Staffing plan

Our staffing plan assigns roles to each member of our project team as follows:

- Dennis Landré - Hardware Team Lead.
- Ihsan Haidari - Hardware Developer.
- Märta Krönström - Software Team Lead.
- Filip Lindhe - Software Developer.
- Jiantao Shen - Software Developer.
- Joel Josefsson - Software Developer.
- Samuel Wågbrant - Software Developer.

Each individual was chosen for their role based on their skills, experience, and interest in the project. Regular meetings will be held to ensure that everyone is on track and to address any concerns that may arise.

11 Project budget

This is an estimation of the project budget, during the process it will develop and products will be added. As the stakeholders of the project already provided most of the necessary hardware equipment the estimation is well within the limit of 20 000 SEK.

Product	Cost (SEK)
Raspberry Pi 4B (8GB)	1400
Raspberry Pi power supply	150
Mounting hardware	1000
Linear actuator	2000
Aluminium profile strut and connecting components	650

12 Development Plan

The development plan provides information about the project, such as our technical approach, methodologies we shall employ and each team member's roles and responsibilities. The plan is designed to make the process of integrating new members easier at any stage of the project.

12.1 Development Methodology

Our team follows a modified version of the linear development methodology model, waterfall. With the waterfall model, each development phase follows a sequential pattern where the following phases can not be started before the previous phase is completed [44]. The waterfall model relies on requirements being defined before any development starts to establish the expected outcome following the development phase's end, see Figure 2. That which differs in our methodology from the traditional waterfall model is that testing will occur after each work package is completed to ensure that potential bugs and misbehaviour of the system are identified as early as possible. To maintain high quality, testing and documentation will occur continuously in each phase.

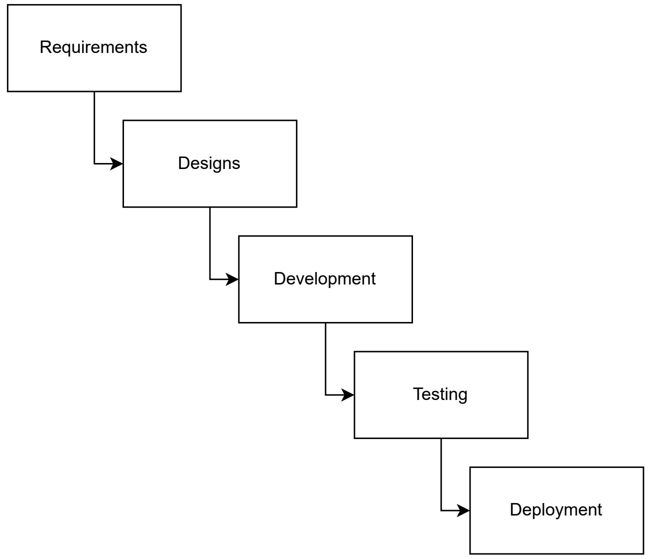

Figure 2: Flowchart of the different stages in the waterfall model

For scheduling and distribution of tasks, the team will use a kanban board [45]. A kanban board helps the team visualise the workflow of the project by using a four-state system, where each task will be in one of four states, see Figure 3. Each individual task will be assigned to a project member or a group of project members, by the team leads, depending on the scope of the task. This process is done through the Task Manager found in Microsoft Teams [46]. When a task has been assigned it is transferred from the To Do stage to the Work in Progress stage where it remains until the task is developed and ready for testing. During the testing stage, it will either pass meaning the task is moved to the Completed state, or fail meaning the task will move back to the Work in Progress state. This system also helps to give an overview of the completed tasks as they are saved in Teams.

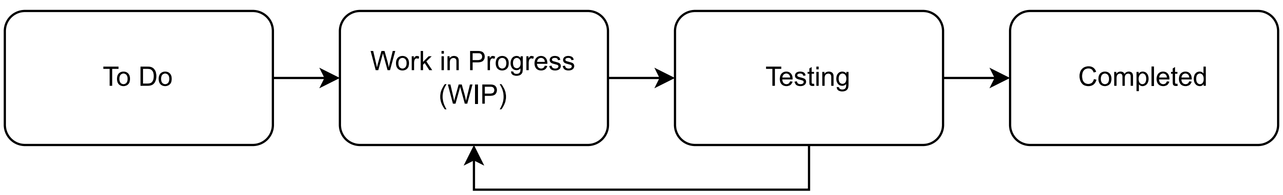

Figure 3: Flowchart of the different states individual tasks assume during development when using a kanban board

12.2 Team Structure and Roles

Our team is comprised of the following roles:

- **Hardware Team Leader** Responsible for the hardware development process and responsible for ensuring that hardware-related requirements are fulfilled. Additional responsibilities are stated in section 10.1.
- **Software Team Leader** Responsible for the software development process and responsible for ensuring that software-related requirements are fulfilled. Additional responsibilities are stated in section 10.1.
- **Hardware Developer** Responsibilities stated in section 10.1
- **Software Developer** Responsibilities stated in section 10.1

12.3 Tools, Technologies, and Systems

We leverage the following tools, technologies, and systems in our project:

- **Software Development Tools:**
  - **Python 3.10.11:** Is used as the main programming language in this project. The reasoning behind using this specific version of Python is that the project will use a library called Open3D which is compatible with Python versions < 3.11. The features that will use Python are surface reconstruction, a GUI, controlling the measurements of the optoNCDT 1402-100 laser sensor, managing the positioning of the antenna, and controlling the movement of the sender robot. If extra communication code is needed, it will be written using Python. Python can be downloaded from [47].

- **Visual studio code:** Is used as the main Integrated Development Environment (IDE) for writing Python code. It can be downloaded here [48].
- **ABB Rapid:** Is used as the main programming language on the ABB SAY to control the arm movement and to host a TCP socket server.
- **RobotStudio:** Is used as a way to simulate and control the robot arm and can be downloaded from [49].

- **Project Management Tools:**
  - **Microsoft Teams:** Is utilised for planning, dividing tasks, storage of material, common calendar, and documentation of the project. It can be downloaded from [46].
- **Documentation and Research tools:**
  - **Overleaf:** Is used as the text editor when writing reports using Latex [50].
  - **Reasearchrabbit** and **Zotero** are used as a way to store and share the papers and reports that we read and use as references in the project. Researchrabbit can be found at [51] and Zotero at [52].
- **Communication Tools:** For effective communication, within the group and towards the supervisors we use Microsoft Teams, which can be downloaded from [46].
- **Hardware Tools and Software:**
  - **SolidWorks:** Is used for 3D modelling, and can be downloaded from [53].
  - **PrusaSlicer:** G-code is generated using the PrusaSlicer software that can be downloaded from [54].
  - **Original Prusa I3 MK3 3D-printer:** It features a removable build plate, an auto-levelling sensor, a Bowden extruder, a workspace volume of 25 x 21 x 21 cm and can only use 1.75 mm PLA/ABS filament [55].
- **Operating Systems:**
  - **Microsoft Windows 10 Education, version 22H2:** Is primarily used on the team's PCs.
  - **Windows CE:** Is used on the Flex pendant for the SAY [56].
  - **Raspberry Pi OS (64-bit) Debian version 11 (Bullseye):** Is used on the Raspberry Pi 4B [57].
- **Hardware:**
  - **Single-Arm YuMi:** Is a collaborative robot with a maximum reach of 0.559m and a payload of 0.5kg [58].
  - **optoNCDT 1402-100:** Is an intelligent laser optical displacement measurement sensor with an integrated signal processor and a measuring range of 100 mm [59].
  - **Raspberry Pi 4:** Is a tiny desktop computer that will run all the finished code.

12.4 Coding Standards and Guidelines

To ensure that the code written for this project achieves high quality, readability, and consistency the Black coding standard for the programming language Python is used [60]. Black follows the PEP 8 coding standard for Python and can be considered a subset of PEP 8. Black allows us to integrate it with GitHub for automatic formatting of the code according to the coding standard. If any RAPID code needs to be written we will use ABB Rapid software development guidelines seen here [61].

12.5 Version Control

We utilise Git to manage changes to our project files and maintain different versions. We use GitHub as a place to store and manage this project's version history. More information on GitHub can be seen here [62]. The link to our repository for this project can be seen here [63].

12.6 Testing and Quality Assurance

Unit testing will be done at the end of each task. And it will be done by the developer who is in charge of the task. Testing and bugs will be recorded according to the testing standards in Section 16. Testing of the entire system will be conducted during the testing stage. The reason for continuous testing is to make sure everything works as intended and to catch any issues early.

12.7 Integration and Deployment

Integration and deployment of the code will be done after each work package is fully completed, including testing, by merging the branch of the work package into the main branch of the repository.

13 Communication plan

The communication plan aims to guide the team members on how communication will be handled throughout the project. Communication throughout the project will primarily be done through physical meetings and Microsoft Teams [46]. Project tasks will be maintained and distributed through Microsoft Teams. This strategic document lays out various aspects of communication, such as the type of information that needs to be distributed, the audience for each type of information, the timing or frequency of communication, and the mediums or channels for transmitting the information.

- **Item/Event:** This refers to the item or event of the communication. For example, daily meetings, stakeholder meetings, or information sharing of issues.
- **Why (Purpose):** This refers to the reason behind the communication. For example, project updates to inform stakeholders about progress, and task assignments may be needed to guide the developers.
- **Who (Target Audience):** This determines who needs to receive specific information. This could include project members such as the hardware and software developers, hardware and software team leaders, and stakeholders.
- **When (Timing):** This indicates when and how frequently the communication should occur. This could be daily, weekly, biweekly, monthly, or at specific project milestones, depending on the nature of the information.
- **How (Communication Channels):** This determines how the information will be delivered. Communication methods include communication software, direct communication, meetings, and project management software.
- **Responsible:** This identifies who is responsible for ensuring the communication happens. This can vary depending on the type of information and the target audience.

Item/Event	Why	Who	When	How	Responsible
Daily meeting	Status of project team members and plan the coming day	Project members	Daily	Physical meetings	Hardware and Software Leads
Weekly meeting	Discuss problems in-depth, plan coming stakeholder meeting	Project members	Weekly	Physical meetings	Hardware and Software Leads
Stakeholder meeting	Keep stakeholders updated, discuss issues and questions	Project members and stakeholders	Weekly	Physical meetings	Hardware and Software Leads
SW Task Assignments	For developers to know their assignment	SW Developer	As needed	Project Management Software	Software Lead
HW Task Assignments	For developers to know their assignment	HW Developer	As needed	Project Management Software	Hardware Lead
Minor issue	If project member needs help with a minor issue	Project members	As needed	Contact team lead or developer with right knowledge	Project members
Major issue	If project member needs help with a major issue	Project members	As needed	Discuss at next daily or weekly meeting	Project members
Information sharing	Information that needs to be shared with the team	Project members	As needed	Microsoft Teams	Project members
Stakeholder forum	If questions for stakeholders arise that can be answered without meeting	Project members and stakeholders	As needed	Microsoft Teams	Project members

14 Risk analysis and response planning

In this section, we describe our risk analysis and response planning as part of our project. The risk score is calculated by multiplying the probability and impact score of a risk, where the probability is ranked from 1, very unlikely to 5, very likely and the impact score is ranked from 1, minimal to 5, critical.
The risk score thresholds are interpreted as follows:

- 1-5: Low priority risks. These are monitored but may not require immediate action.
- 6-10: Medium priority risks. These require a mitigation plan and should be addressed as resources allow.

- 11-15: High priority risks. These require a detailed mitigation plan, and resources should be allocated to address these risks immediately.
- 16-25: Critical risks. These must be addressed immediately with a detailed and efficient mitigation plan to avoid severe project disruption.

The table below outlines the identified risks, their evaluation, and planned responses:

Risk	Probability(1 to 5)	Impact(1 to 5)	Risk(P*I)	Risk Response
Critical team member leaves during the project	2	5	10	Develop contingency plan, cross-train team members
Scope creep leading to project delay	1	4	4	Regular scope review, robust change management process
Technology becomes obsolete	1	4	4	Regularly update technological skill sets, maintain flexibility in tech stack
Software bugs detected after deployment	3	5	15	Rigorous testing process, allocate resources for post-deployment bug fixes
Unexpected budget cuts	1	3	3	Prepare a flexible budget that can accommodate cuts, regular financial reviews
SAY positioning not repeatable enough	3	5	15	Test the repeatability at an early stage and prepare contacts with ABB
One measurement sensor is not good enough for object reconstruction	3	4	12	Test the accuracy at an early stage and research alternative solutions
Hardware malfunctions requiring spare parts or replacements	2	4	8	Test hardware at an early stage to identify problems, prepare contacts with suppliers
Unexpected delay occurs for ordered components	2	5	10	Develop contingency plans, identify alternative components and suppliers
Unexpected delay in a dependent work package is causing a delay in the subsequent work package	3	4	12	Reassess the schedule and consider reallocating resources to speed up the delayed work package or the subsequent work package.

15 Documentation plan

The documentation plan outlines the fundamental guidelines for recording and preserving important information throughout the project's duration. This plan provides details about what should be documented, how to document, when to document, the responsible party, and where to document.

15.1 What to Document

- Code comments **shall** be written in all code.
- Meeting notes for group meetings.
- Meeting notes for supervision meetings.
- User manuals **shall** be documented to make sure everyone can operate the system, run any code, and test any equipment.

15.2 How to Document

- Code comments will be done in such a way that it is easy to understand how the code functions and it should be done according to the PEP-8 standard. See more information under section 12.4.
- Meeting notes will be written in such a way that they are easy to understand by everyone. If there is any ambiguity or questions regarding the notes than the members can ask the software team lead.
- User manuals will be documented in such a way that regardless of previous experience anyone should be able to follow the manual. Template for user manuals can be found in the GitHub repository under the folder Documents and is written using the text format Markdown.

15.3 When to Document

- Code comments will be continuously written to make sure that anyone can take over the development of the code.
- Meeting notes for group meetings will be documented when deemed necessary by the software team leader.
- Meeting notes for supervision meetings will be documented for each meeting within 24 hours.
- User manuals will be documented when the specific part related to the user manual is complete and functional.

15.4 Who is Responsible

Assign documentation duties to specific roles:

- **Hardware Team Leader:** Oversees and approves hardware-related documentation tasks.
- **Software Team Leader:** Oversees and approves software-related documentation tasks. Documents meetings.
- **Hardware Developer:** Creates and updates hardware-related documentation as assigned.
- **Software Developer:** Creates and updates software-related documentation as assigned.

15.5 Where to Store Documents

Documents will be stored in Microsoft Teams and on the GitHub repository. This is done to make sure it is easy to access by team members, stakeholders, and the examiner.

15.6 Document Review Process

Software- and hardware team leaders will review documents and task status weekly during the testing phase of the waterfall approach. When the system meets all requirements or enters its final week of testing phase, all team members will also review the documents to ensure they are understandable.

15.7 Training

Each team member is updated on the documentation process at the start of the project, or if a new team member is added they will be introduced to the documentation when they start.

16 Testing Plan

The testing plan documents the details of the testing strategy, tools and methodology that be used will use in the project. Its purpose is to help team members ensure that their work meets the requirements of the project.

16.1 Testing Methodology

During this project, manual testing is employed because an automated testing tool is expensive. Manual testing is both cost and time-efficient for smaller projects with limited budgets which benefits us. With manual testing, we are also able to create a large variety of tests not possible with automated tests.
Software testing methodology:

- **Unit test:** Our team performs unit tests to ensure there are no bugs or issues in certain parts of the system. Unit testing is when different parts of the system are tested individually. This methodology has been chosen due to its benefit that confirms every part of the system works as intended.
- **Integration test:** Our team performs integration tests to ensure that the GUI and the back-end can operate without issues. This methodology has been chosen to verify there are no issues between the GUI and the back-end systems.
- **System test:** Our team performs system tests to ensure the whole system, including hardware, operates without problem. This methodology has been chosen to verify that the final system works as intended.

- **Acceptance test:** Our team performs acceptance tests to ensure the whole system, including hardware, meets all requirements. This methodology has been chosen to verify our final system meets all functional and non-functional requirements.

Hardware testing methodology:

- **Design validation:** Our team follows the design validation to ensure the hardware meets the requirements. This methodology has been chosen due to its benefit that confirm 3D-printed model works correctly in the system.

16.2 Testing Team Structure and Roles

In our team, everyone is both testing team leader and test engineer in their own task:

- **Testing Team Leader:** Collaborates with both software and hardware teams to ensure the testing is completed on time.

- **Test Engineer:** Formulates and implements test case. Documents results and reports them in the team meetings.

16.3 Testing Tools, Technologies, and Systems

The testing tools that will be used in the testing process:

- **Bug Tracking Tools:** Microsoft Excel will be used to log bugs and track their status. Microsoft Excel can be downloaded from Microsoft Office 365 [64].

- **Test Management Tools:** Microsoft Excel will be used to document the testing process and results. It can be downloaded from Microsoft Office 365 [64].

16.4 Testing Standards and Guidelines

Create a test report template using Microsoft Excel to ensure consistency in the testing reports. The file is stored on GitHub [63].

16.5 Version Control for Test Artefacts

GitHub is the platform that will be used for managing modification of our test artefacts and storing different versions [63].

16.6 Bug Reporting and Tracking

A bug report file is created using Microsoft Excel. Every team member is responsible for reporting bugs in the file in GitHub [63].

16.7 Test Schedule

Unit testing should be performed after completing a part of the system. The system and acceptance testing will be performed after completing all main parts of the system.

16.8 Integration and Regression Testing

The integration and regression testing is performed once a function successfully passes the unit testing and merges with other functions.

17 Handover plan

The handover plan describes how the system will be delivered to the stakeholders at the end of the project. This includes who is responsible for what, what to deliver and how, and where the artefacts are located.

17.1 Handover Methodology

Our handover methodology includes:

- Inventory check to ensure all equipment received from the stakeholders and purchased equipment is returned to the stakeholders.

- All code and relevant files will be available via the public GitHub repository owned by MDU-C2 [63].

- Finalised documentation which includes; a final report for the project and documentation for use of the system, including hardware and software subsystems.

- Presentation for stakeholders, to ensure that the stakeholders are comfortable operating the presented deliverable.

These steps have been chosen to ensure a comprehensive and efficient handover process.

17.2 Handover Team Structure and Roles

Our handover team includes the following roles:

- **Handover Team Leader:** Schedules meetings with the stakeholders during the handover process. Responsible for handing over all deliverables.
- **Handover Specialist:** Ensures that the project owners are comfortable operating and understanding the project's deliverables.

17.3 Handover Tools, Technologies, and Systems

The following tools are used in the handover process:

- **Inventory Management Tools:** We utilize Microsoft Excel to catalogue and track all equipment and project deliverables for handover, which can be downloaded from [64].
- **Presentation Tools:** If necessary, we use Microsoft PowerPoint to conduct presentations or demonstrations, which can be downloaded from [65].

17.4 Handover Schedule

Our handover schedule aligns with the overall project timeline. The handover is planned to align with the termination of the project. The handover schedule can be found in our project timeline, see section **??**.

17.5 Documentation

All project documentation, including manuals, technical documentation and reports can be accessed by the project owners in the GitHub repository [63].

17.6 Presentation and Demonstration

Our team will ensure the project owners are familiar with the project's operation and results with a presentation and demonstration preceding the handover.

17.7 Final Sign-off

Following a final meeting issued together with the project owners, the project owners will sign off, confirming the handover is complete.

17.8 Version Control for Handover Artefacts

We utilize Git to manage changes to our handover artefacts and maintain different versions. The repository used for this project can be found on GitHub [63]

17.9 Follow-up and Feedback

We value feedback from the project owners and have a process for follow-up. Follow-up questions from the project owners following the end of the project should first and foremost be directed to the hardware and software team leads of the project. Depending on the nature of the question, project owners may contact a developer directly if the project owners know that the developer is knowledgeable regarding the topic of the questions. This process ensures that all aspects of the handover are completed satisfactorily and addresses any potential concerns post-hand-over.

18 Individual contributions

Dennis Landré: Hardware requirements, project budget, risk analysis and response planning, hardware tools and software, hardware
Ihsan Haidari: State of the art, risk analysis and response planning, project budget
Märta Krönström: Executive summary, scope, milestone plan, work breakdown structure, schedule, SWOT-analysis, project budget
Samuel Wågbrant: Software and project requirements, SWOT-analysis, communication-plan, handover plan
Filip Lindhe: Purpose, Goal, Limitations, Roles, responsibilities and authorities, Development Methodology, Tools, Technologies and Systems, Coding Standards and Guidelines, Version Control, Testing and Quality Assurance, Part of Communication plan, Documentation plan
Joel Josefsson: Background, stakeholder mapping, part of Executive summary, Roles, responsibilities and authorities and SWOT-analysis
Jiantao Shen: Software product requirements, non-functional requirements in hardware requirement, testing plan, SWOT-analysis
Everyone: Corrected grammar and spelling throughout the document. Also, preformed some minor changes to other parts.

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