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
1.1.3.1	Deliverable	Set up the new frame
1.1.3.1.1	Task	Mount all the boards and aluminum profile

9.1 Work breakdown structure

ID	Type	Activity
1.1.3.1.2	Task	Adding features for robustness
1.1.3.1.3	Task	Safety features
1.1.3.1.4	Task	Equipment placement
1.1.3.1.5	Task	Cable management
1.1.3.1.6	Task	Hole for breast phantom
1.1.3.4	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

9.1 Work breakdown structure

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

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.

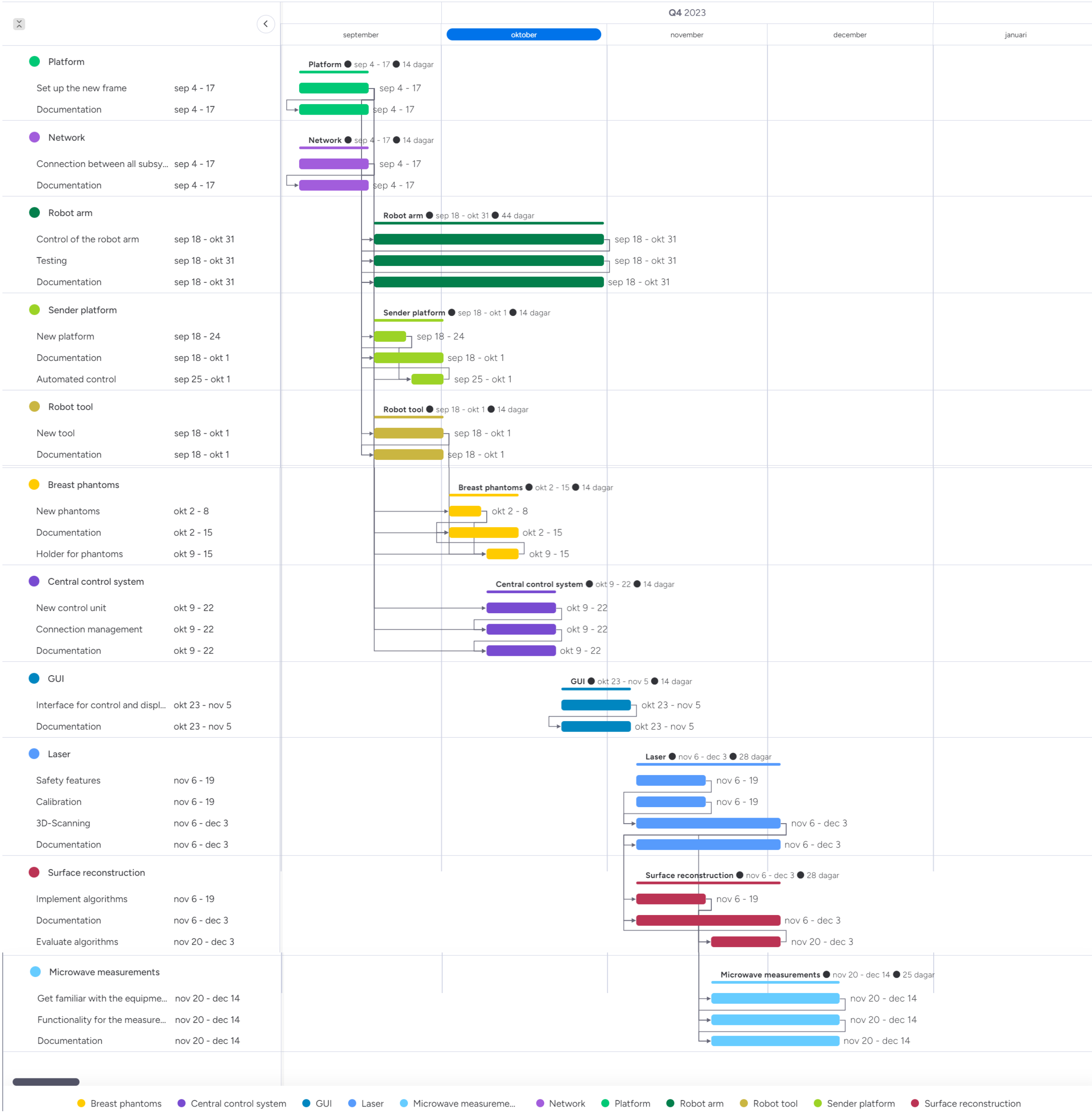

Figure 1: Gantt chart displaying an approximation of the timeline for the project.

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.

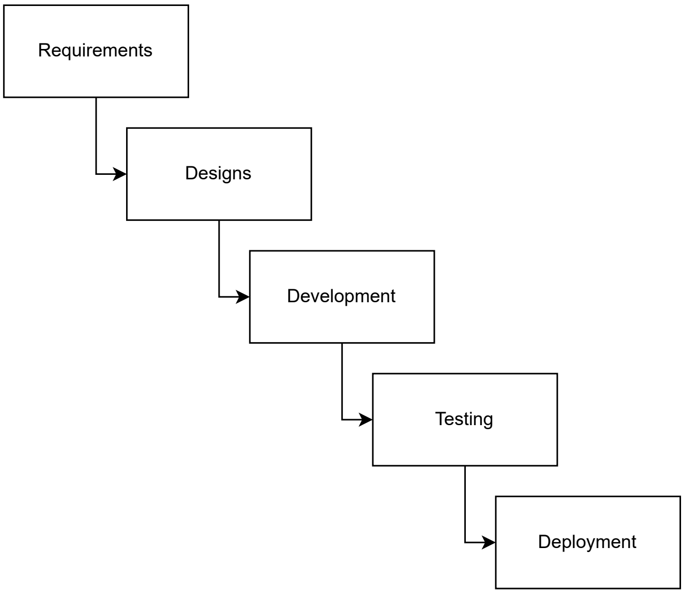

Figure 2: Flowchart of the different stages in the waterfall model

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.

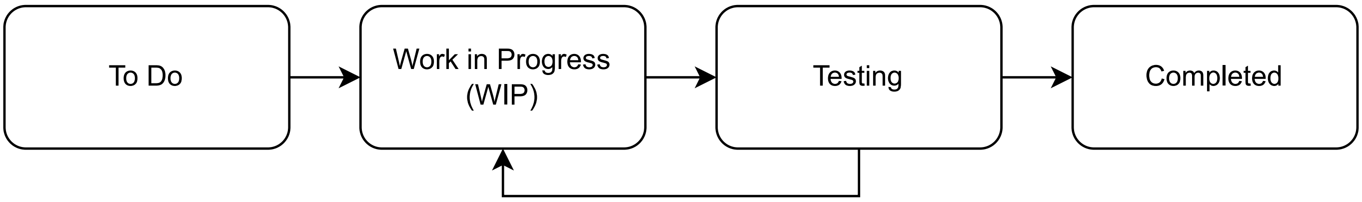

Figure 3: Flowchart of the different states individual tasks assume during development when using a kanban board

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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