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Development of an Autonomous Open-Source Inventory Performance Robot for the University of Tartu Library

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Development of an Autonomous Open-Source Inventory Performance Robot for the University of Tartu Library

Inventory management is crucial for the successful functioning of a venue. Manual inventory management and asset tracking can be time-consuming, dull, and inefficient. In particular, in large-scale libraries, it can take personnel months to perform a single inventory round of all the books. Nowadays, using advanced robotics solutions, it is possible to automate the process and provide more accurate information on the availability and location of the desired book. This results in higher satisfaction for librarians and visitors, as they can successfully find the books of interest.

This thesis aims to create an open-source solution that contains a radio frequency identification system for the University of Tartu library. The result is intended to use the Robotont project as a base platform. It should be able to autonomously navigate through library halls while scanning the bookshelves and adjusting the antenna height for it to be at the same level as the books. Simultaneously, it should document the book IDs and their location to produce a heat map containing the most probable location for each book.

Keywords:

RFID, inventory, autonomous, ROS2, Robotont, asset tracking, SLAM, NAV2, library

CERCS: T125; Automation, robotics, control engineering

Institute name: Institute of Bioengineering

Research group: Intelligent Materials and Systems Lab, Institute of Technology

Tartu Ülikooli Raamatukogu autonoomse ROS2-ga ühilduva inventari jõudlusroboti väljatöötamine Autonoomse ROS2 võimekusega inventuuri roboti välja töötamine Tartu Ülikooli raamatukogule.

Inventari haldamine mängib olulist rolli igas asutuses. Käsitsi varude haldamine ja varade jälgimine võib olla aeganõudev, tüütu ja ebaefektiivne. Eelkõige suuremahulistes raamatukogudes võib kõigi raamatute ühe inventuuriringi läbiviimiseks kuluda mitu kuud. Tänapäeval võimaldavad täiustatud robootikalahendused seda protsessi automatiseerida pakkudes täpsemat infot soovitud raamatu saadavuse ja asukoha kohta. Selle tulemusel suureneb nii raamatukoguhoidjate kui ka külastajate rahulolu, sest huvipakkuvad raamatud on hõlpsamini leitavad.

Käesoleva lõputöö eesmärk on luua ROS2-ga ühilduv lahendus, mis sisaldab raadiosagedustuvastussüsteemi (RFID) ning on mõeldud kasutamiseks Tartu Ülikooli raamatukogus. Lahendus tugineb avatud riistvara ja lähtekoodiga projektile Robotont, mida kasutatakse baasplatvormina. Platvorm peaks suutma iseseisvalt navigeerida läbi raamatukogu saali, skaneerides samal ajal raamaturiiuleid ja reguleerides antenni kõrgust vastavalt riiulite kõrgusele, et see oleks raamatutega samal tasemel. Samal ajal peaks see dokumenteerima raamatute elektroonilised märgised ja nende asukohad, et koostada kaartiga raamatu kõige tõenäolisema asukohaga.

Võtmesõnad:

RFID, inventar, inventuur, autonoomsus, ROS2, robotont, SLAM, NAV2

CERCS: T125; Automatiseerimine, robootika, juhtimistehnika

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TABLE OF CONTENTS

TERMS, ABBREVIATIONS AND NOTATIONS

ABS - Acrylonitrile Butadiene Styrene

AM - Additive Manufacturing

CAD - Computer Aided Design

EOL - End Of Life

HF - High Frequency

IC - Integrated Circuit

ISO - International Organization for Standardization

LF - Low Frequency

NFC - Near Field Communication

PETG - Polyethylene Terephthalate Glycol

PLA - Polylactic Acid

QR - Quick Response

RF - Radio Frequency

RFID - Radio Frequency Identification

ROS - Robot Operating System

UAV - Unmanned Aerial Vehicle

UGV - Unmanned Ground Vehicle

UHF - Ultra High Frequency

UML - Unified Modelling Language

INTRODUCTION

Inventory management and asset tracking are done everywhere, from retail stores to large-scale factories and libraries. More complex, large-scale supply chains that need accurate and real-time inventory information are stimulating the growth of this market [1]. Inventory management is done to keep track of the available items and, at times, determine their location, which helps companies be aware of the physical stock. The methods have advanced significantly from handwritten notes and counting items manually millennia ago [2] to automated solutions and human-robot collaboration nowadays.

While these automated solutions are appearing, this task is still often done by humans and is time-consuming, with a low accuracy [3], monotone, and frequently has low job satisfaction [4]. With the advancements of 21st-century robotics, it has become possible to automate this process. The benefits are evident, with the efficiency and accuracy of the robotic solution surpassing that of a human [5] and the job satisfaction for people working alongside robots increasing [4]. Additionally, robots do not get tired and only need to stop to get charged, meaning they can also work at night, making this solution more time-efficient. Acknowledging the need for change in this area in the last decade, multiple solutions have been created using different tools, approaches and aims.

Commercially available solutions are often difficult to customize, rely on outdated software, and may offer poor customer support, or disappear entirely if the vendor goes out of business. They can also be challenging to combine with the existing library database. An open-source alternative addresses these issues by allowing customization, easy integration with the current database, and long-term sustainability.

This thesis aims to create an open-sourcce robotic solution for autonomously performing inventory reading in the University of Tartu library. The solution should be adjustable to different robotic systems equipped with a wheelbase and using standard robotic software - Robot Operating System 2 (ROS2). The end solution is intended to be capable of creating a map and using it for navigation while scanning the Radio Frequency Identification tags (RFID). The data will be processed to enable visualisation of the most probable location of each book on the map. This will result in a more timely book inventory and easier locating of the sought-after book.

1 LITERATURE REVIEW

1.1 Inventory Automation Solutions

In recent years, the number of solutions to automate the inventory processes has increased significantly. These solutions can be broadly classified as either static or mobile, where mobile systems use Unmanned Ground Vehicles (UGVs) or Unmanned Aerial Vehicles (UAVs) for navigation. Different tag-accessing principles are used - barcode scanning, RFID, Near Field Communication (NFC), and visual image recognition. The inventory solutions that dominate the market use RFID[6] tags and are either static or use UGVs. These systems differ in several parameters, such as the robot's battery life and charging possibilities, price, size, human-robot interface, and detection precision.

Figure 1: Different autonomous asset tracking solutions. 1 - Cyeko UHF RFID Portal Gate; 2 - MetraLabs TORY® RFID mobile robot; 3 - CribMaster AccuCab Automated Tool Cabinet[7]; 4 - Quadraceptor used as UJI Aerial Librarian Robot

One of the simplest and most straightforward implementations of inventory management is an RFID portal gate (Figure 1.1) [9]. The portal has different variations in size and antenna placement; however, the main characteristic is that the gate is static and can detect multiple tags simultaneously passing through it. It is often used in factories or in large warehouses to scan tags going along a conveyor belt. Another area where RFID gates have proven themselves valuable [10] is in retail stores - the gates that are crossed entering and exiting the store are also usually equipped with RFID readers and can detect items brought through them, which is helpful in theft prevention.

Multiple companies [11, 12] offer RFID gates that promise over 99% accuracy. As gates are powered from a wall outlet, they are able to work continuously. This solution is great for instances where there are many tags, and it is not vital to know how the tags are located. A negative aspect of the RFID gateway is that it is not easily adjustable for every situation, and the item location determination precision is low. If there is already a functioning venue with items that need to be tracked, it is more challenging to implement this solution, as the flow of items needs to be constrained to go through the gates. Positively, there are other solutions that can be easily adjusted to work in different areas / systems and provide a better localisation precision.

The first idea of an automated inventory solution to precisely determine the item's location appeared as early as 2007 [14] when a simple High Frequency (HF) RFID antenna was attached to a mobile robot that could drive past shelves and localise tags. In 2025, the complexity of robots has increased, and they are capable of navigating autonomously, changing antenna height, charging themselves, and performing faster and more accurately. One such mobile robot is TORY (from the word inventory), made by MetraLabs (Figure 1.2) [13]. TORY was tested in the library of the Max Planck Institute, where in one one-hour time frame, it detected 35,000 books with a precision of 99.11% [14] - meaning that only around 0.89% of books were not detected. TORY shows success and is actively used in retail stores in New Zealand and Australia [15], where it provides 95% accuracy in inventory in “Kmart” stores, compared to 60% that resulted from manual work.

Another highly adjustable robotic solution uses a quadcopter that performs the inventory aerially. One such development is the UJI Aerial Librarian Robot [8]. This robot uses a drone to navigate the library and computer vision to detect books. Making an RFID-based system, as in the previous examples, can be costly and require multiple components. By using computer vision, this robot can be used for different goals and is comparatively easier to implement. A great benefit of a UAV is that it can traverse three-dimensional space, move comparatively faster than a UGV, and generally take up less space [16]. The most significant setback in using UAVs for inventory management is that there are higher upfront costs, and the complexity of the control results in reduced reliability of the system.

It is crucial to analyse each situation individually to determine what solution would be the most appropriate and efficient. Cost can be an essential factor when choosing the right solution. For example, implementing a new large-scale RFID system requires purchasing tags, readers and antennas, installing the system, and maintaining both hardware and software, creating a substantial amount. The precision of the inventory is important as well, and it has to be decided what precision level is required. Additionally, factors such as speed of inventory performance, how reliable and safe the solution is around people, and the dimensions of the area needing to be inventoried must be considered.

1.2 Object Identification Methods

There are different ways to identify inventory - visually by reading the name of the item, using Quick Response (QR) codes, using barcode technology, or using communication technologies such as NFC and RFID. Nowadays, barcode and RFID technologies are used most frequently, as they are less prone to human errors and have a higher efficiency compared to traditional inventory methods [17].

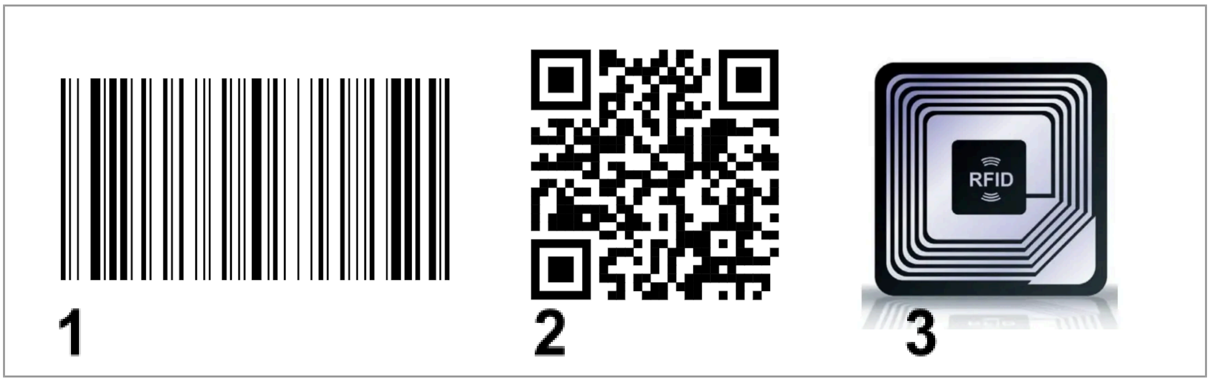


Figure 2: 1- Barcode; 2- QR code; 3- RFID tag

1.2.1 Optical Labels

Barcodes and QR codes are optical labels that differ in their dimensions - barcodes (Figure 2.1) [18] are one-dimensional, meaning they can be read only horizontally. In contrast, QR codes (Figure 2.2) can also provide information vertically.
Barcodes are mainly used when there is no need for excessive data to be contained in the tag [19]. For example, they are often used repetitively on the same products in stores, where there is no need for unique information for each product. They are cheaper to install and take less scanning time, making them suitable for large-scale settings. The negative aspects are that they can only be scanned from one dimension, and if the barcode is slightly damaged, it will not be possible to obtain the information that it stores [20].
On the other hand, QR codes offer considerable versatility in the quantity of information they can contain. The QR codes can be encrypted, making them more suitable for instances where

more security is required, such as digital payments. An advantage of QR codes is that they can be easily scanned using most mobile phones, although barcode scanning in this way has also become increasingly common.

1.2.2 RFID

RFID technology has increased significantly in the recent decade, becoming a feasible alternative for barcodes [21]. The ability to communicate through obstacles and without the tag being in the line of sight is one of the most significant advantages of this approach. The main components of an RFID system are an RFID reader and RFID tags (Figure 2.3) [22] - also called transponders. The basic principle of the RFID system (Figure 3) [23] is that the reader sends out a Radio Frequency (RF) signal. A tag receives the signal, which energises the tag to send a signal containing the assigned ID code of the item back to the reader, which then communicates the ID to the host device [24].

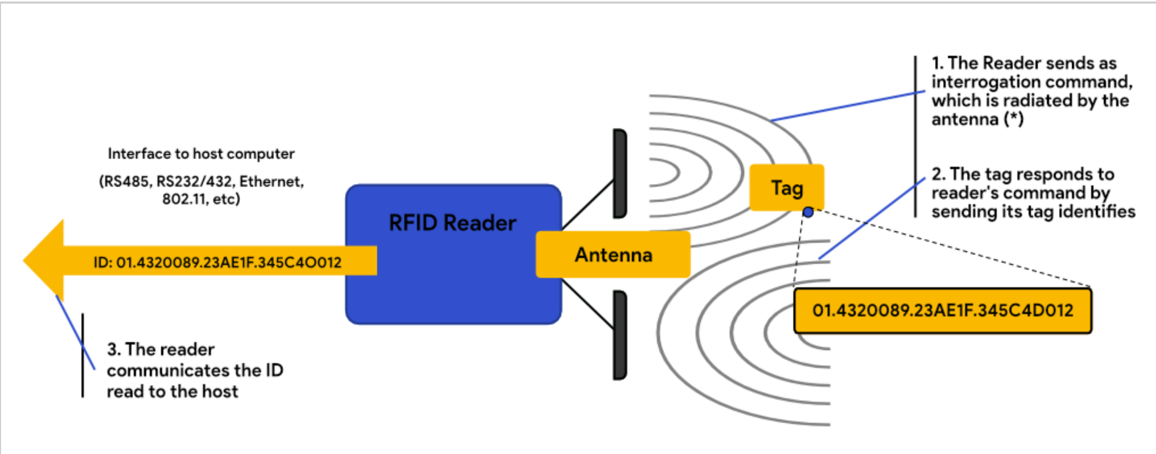


Figure 3: General working principle of an RFID system

The RFID tags include an in-built antenna, an integrated circuit (IC) and a substrate that holds the other components of the tag together (Figure 4.1) [25]. The tags can be either active or passive. The active tags have their own power source, such as a battery, while the passive tags use energy from the reader's antenna to gain power [26]. This mode of communication uses a kind of coupling, and it entails that the passive tag first receives energy from the emitted electromagnetic waves of the RFID reader. Then, the energy goes through the tag's antenna and activates the IC, which alternates the signal to include the needed data. Lastly, the tag's antenna sends it back to the reader's antenna [27].

There are three main types of RFID systems: LF (Low Frequency), HF, and UHF (Ultra High Frequency). They differ in their operating frequency range, which impacts other characteristics of the system, such as reading distance, material throughput, and transmission speed (Table 1) [28, 29]. While each of these ranges is best suited for different applications, nowadays, the UHF RFID system is becoming the most used one, as it reaches the farthest, offers the fastest data transmission speed, and can read multiple tags simultaneously. Usually, in the context of RF, an increasing signal frequency results in decreased travel distance; however, the UHF system has a higher frequency than HF and can still reach tags further away. This happens because HF RFID systems use near-field (inductive) coupling, while UHF systems use far-field (backscatter) coupling [30].

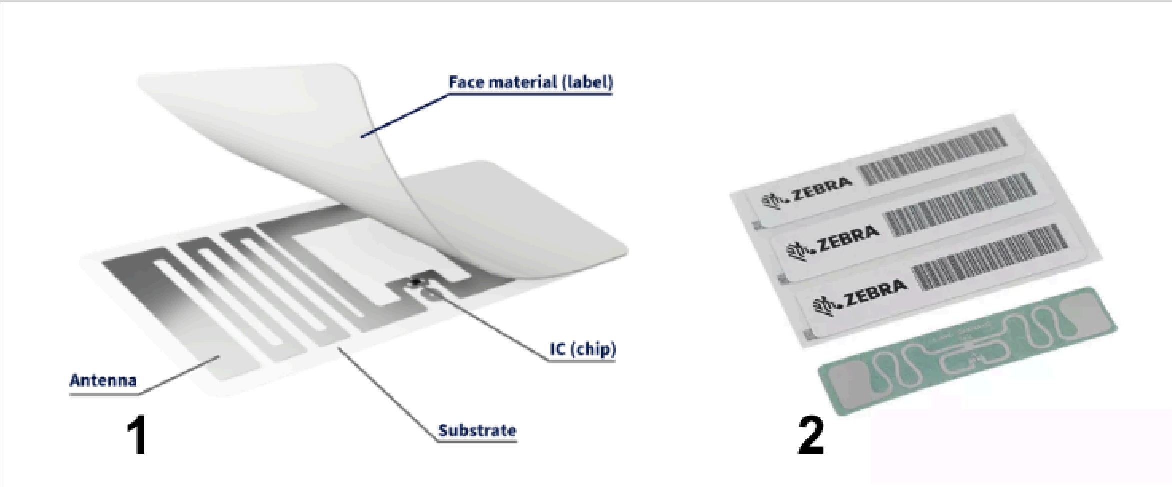


Figure 4: 1- structure of an RFID tag; 2- example of real-life RFID tags

Table 1: Comparison between LF, HF, and UHF RFID systems

	LF	**HF**	**UHF**
Typical operating frequency	125-134.3 KHz	13.56 MHz	860-960 MHz
Read range (m)	<0.1	0.1-1	1 - 12
Multiple tag reading capability	usually none	good	excellent
Data transmission rate	slow	moderate	fast
Common use cases	Access control, animal identification,	contactless payment, library books	inventory control, asset tracking

Similarly to different RFID systems, there are also different standards and guidelines a system must follow. Following them ensures that systems are interoperable no matter the vendor [31]. For UHF RFID systems, the most internationally used standard is ISO / IEC 18000-63 (Originally called ISO 18000-6C, but now known as ISO/IEC 18000-63 due to a change in ISO naming rules). It defines the communication between interrogators and tags in the 860 MHz to 960 MHz range [32], meaning that if both the reader and tags follow this standard, they will be compatible.

Some factors can make the inventory process using RFID unsuccessful. The biggest issue is materials (such as liquid or metal) that can interfere with the tags and block the signal. Additionally, the position of the tags can determine the success rate of the detection, meaning that efforts need to be taken to place the tagged items in the right position [33].

Overall, RFID systems have shown great success and are being implemented in more places. For example, a clothing store, "Uniqlo", has implemented RFID in the clothing tags, speeding up customer checkout time by 50% [21] and leaving the customers positively surprised about the advanced system.

1.3 Robotics solutions

Combining hardware, electronics, and software in a time of fast-evolving robotics can be a time-consuming and challenging task if one needs to start from scratch. Luckily, many already existing robotics solutions and tools make the prototyping process smoother.

1.3.1 ROS2

One of these tools is the open-source Robot Operating System (ROS) [34]. It is a software that contains tools, libraries and capabilities to help create robotics applications. It has proven to be an industry standard and is actively used in many large-scale industries, including Boeing, BMW, Intel and Panasonic [35]. ROS originated in 2010, and multiple distributions have been released [36]. In 2015, the first version of ROS2 was released, and now the only supported versions are ROS2 Jazzy Jalisco, with end-of-life (EOL) expected in 2029, and ROS2 Humble Hawksbill, with expected EOL in 2027 [37]. With ROS2 being 100% open-source and compatible with Linux, Windows, and macOS, it is an excellent tool for robotics projects. A great benefit that ROS2 offers is that it is easy to connect different systems, both hardware and software, if they use ROS2 since they utilise the same standard methods.

ROS2 works on the basis of communication between nodes, which are individual units of computation [38]. There are different modes of communication between nodes, such as subscriber/publisher and client/server (Figure 5) [39]. The simplest is subscriber-publisher communication, in which the publishing node publishes/sends a message of the needed type on a specific topic. The subscriber node is always listening to this topic, and when a message is published, it receives it from the topic. This enables any subscriber and publisher node to communicate with each other if they are assigned to the same topic. This method of node communication does not involve feedback, meaning that the publisher node has no information about whether the task sent to the topic was received and successfully completed. To solve this, services can be used [40]. As seen in Figure 5, the service works by the service client requesting a service, the service server completing the task and sending a response containing the task outcome back to the client.

There are more modes of communication, such as Actions, which are more complex and are mostly based on principles similar to those previously mentioned.

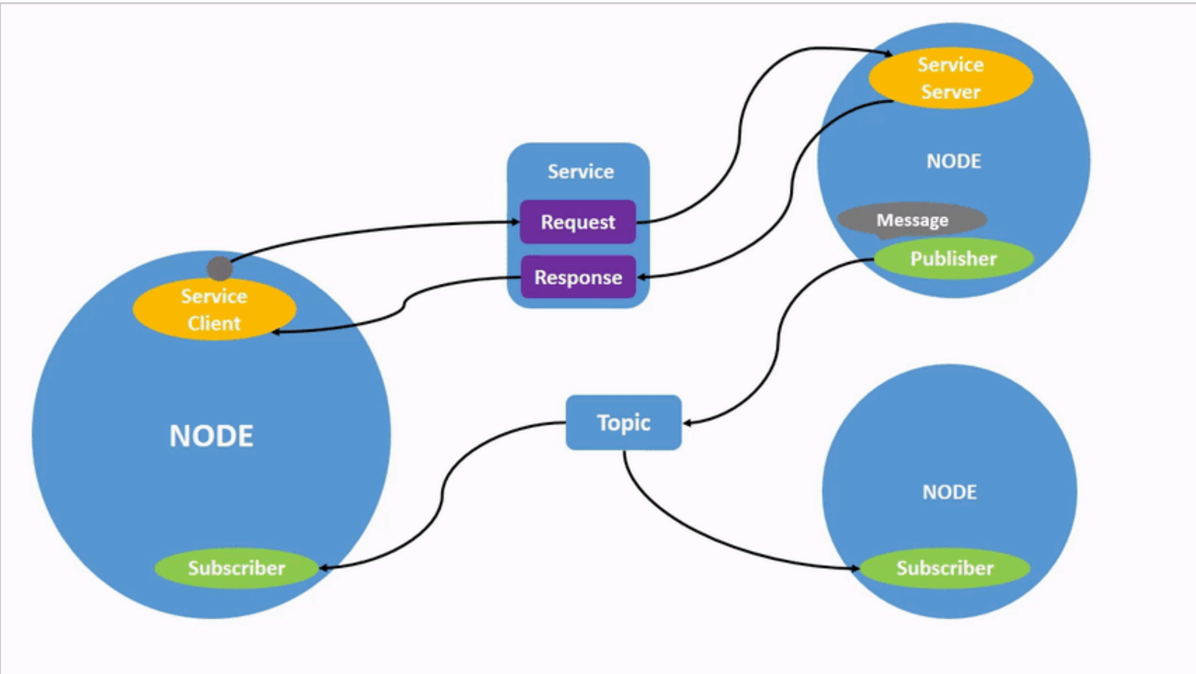


Figure 5: Communication between nodes in ROS2

1.3.2 Additive Manufacturing

Additive manufacturing (AM) is another tool that can significantly improve the prototyping process. It enables a fast, precise and accessible way to produce new parts. AM can create a geometrically demanding part layer by layer, differing from the traditional manufacturing process that involves forming the part by removing excess material [41]. There are seven standardised types of AM methods [42], the most frequently used one being Fused Deposition Modelling (FDM), which is often used under the wider category name - 3D printing.

FDM works by using the extrusion principle (Figure 6) [43]. It takes polymers in the form of a filament, heats them to their melting temperature and deposits the melted material on a heated plate layer by layer, following the provided path that is generated using a CAD program [44]. After the temperature of the polymer decreases, it solidifies again and stays in the printed shape. Different materials can be used as the filament, with some of the most popular ones being Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate Glycol (PETG) [45]. The composition of these polymers differs, meaning that the characteristics, such as tensile strength, flexibility, and biodegradability, of the end part will be different.

When designing a part, it is essential to choose the right material to ensure that the part is durable and suitable for its purpose [46]. For example, PLA is less likely to result in failed printing and can be printed faster. It also creates a smoother finish and is less expensive, making it more suitable for large static parts. On the other hand, PETG is more durable and flexible- it is better suited for functional parts under considerable stress.

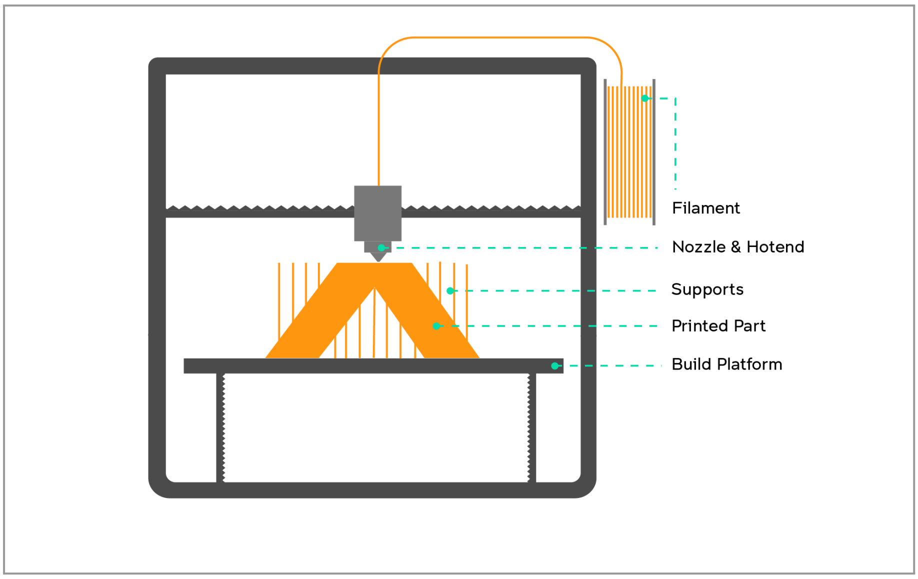


Figure 6: FDM working principle

1.3.3 Robotont

When trying to create a new project, it is worth using an already existing open-source solution as a base. This significantly speeds up the prototyping process and allows for the development of more advanced outcomes, as time and resources do not need to be spent reinventing existing components. One such platform that is already used as a base for other projects is Robotont.

Robotont (Figure 7) [47] is an open-source robot used in education and research in the field of robotics, made in collaboration with the University of Tartu. It is ROS compatible (migrating from ROS1 to ROS2 Jazzy) and can be used both with a real-life physical Robotont as well as with only a simulation. Since it is open-source, all the necessary tools for understanding the robot are found on the Robotonts GitHub page, which provides the robot's software, hardware, and electronics data. A beneficial feature of Robotont is the possibility of simple connectivity with external devices. On the PCB, there is a dedicated power connector that can provide 3.3 V, 5 V, and 12 V, ensuring compatibility with most DC-powered devices. The parts of the robot are primarily produced by additive manufacturing; therefore, if they need to be adjusted, it is easily done by downloading the part from the GitHub page and modifying it in a computer-aided design (CAD) tool.

As a result of the mentioned features, it is easy to connect Robotont with other devices, change the hardware of it, as well as connect it with existing ROS systems, making it a great platform to use as a base for other work.

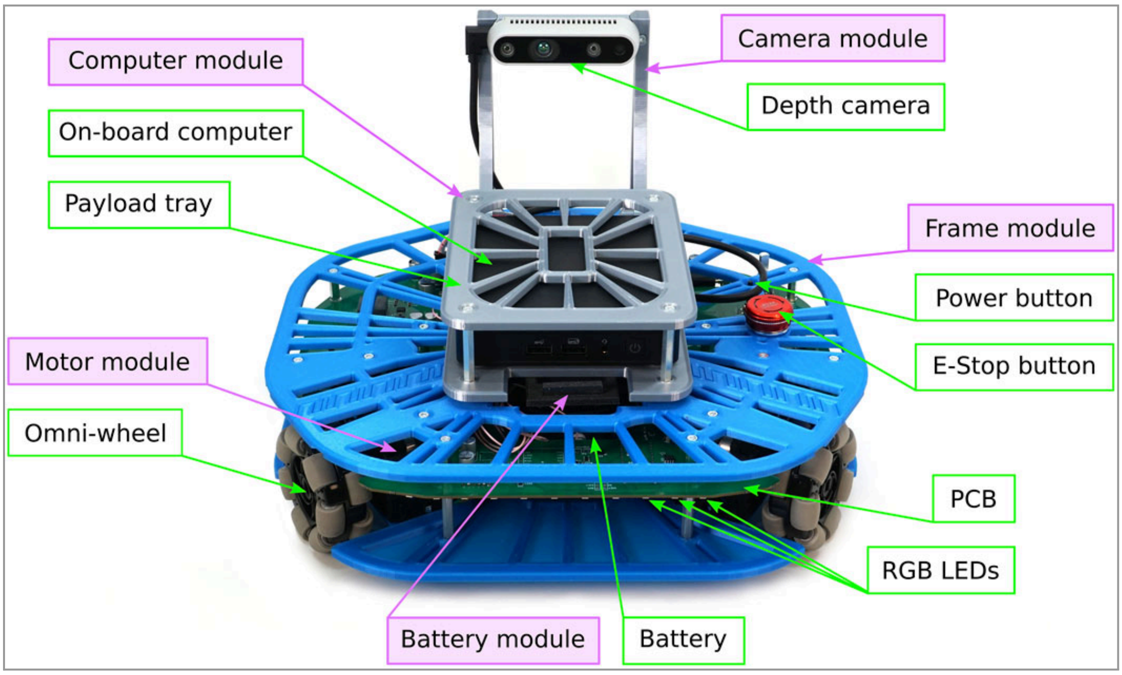


Figure 7: Main component of the third generation Robotont

2 AIM OF THE THESIS

The aim of this thesis is to develop an autonomous ROS2-compatible inventory performing system for use in the University of Tartu library, utilising an open-source approach. The system integrates autonomous navigation with RFID tag reading capabilities and includes a mechanical solution for adjusting the height of the antenna to make it possible to scan books from shelves at different heights.

2.1 Research objectives

To achieve this aim, the following objectives have been defined:

1. Develop ROS2-based software that enables autonomous navigation and RFID tag reading during movement.

2. Design and build a mechanical system for adjusting the RFID antenna height to match various shelf levels.

3. Integrate and test the complete system in the real environment of the University of Tartu library.

2.2 Requirements

To successfully reach the research aim, certain requirements need to be set (Table 2). Following them ensures that the developed system meets the necessary standards.

Table 2: Requirements that must be followed together with their justification

No.	Requirement	Reasoning
1	UHF RFID system.	Currently, UHF RFID tags are used in the library, and the new system has to be compatible with them. Both the chosen antenna and the reader module have to function within Europe's set UHF regulation, 860-960 MHz.
2	Adjustable antenna height	The bookshelves are up to 2 meters high, and to create a precise inventory system, it is important to have the possibility to change the height of the antenna.
3	ROS2 compatibility	The created solution has to be compatible with ROS2 Jazzy Jalisco [48], as it is the current industry standard. This ensures long-term maintainability and support for further integration with other ROS2 systems.
4	Autonomity	The goal of this thesis is to create a way for inventory to be automated and use as little human labour as possible. This means that after receiving the initial input, the robot must be capable of performing a full inventory round without any human intervention.
5	Open-source	Open-source projects greatly benefit future research and innovation, as they give a starting point on which to build. To contribute to research, the created solution has to be open source- CAD files, ROS2 code and instructions must be published to GitHub to make the full replication of the system possible.
6	Reliable output of the book's height and location.	Same as in the inventory done by humans, the output must provide information about where on the map and how high the book is located.

3 RESEARCH AND DEVELOPMENT

Overall, there are many parts in this thesis that need to be connected to achieve the final result. Electronics, hardware parts and software all need to function together. From the hardware side of the project, new parts have to be created to implement the height adjustment system. In terms of electronics, a suitable RFID reader system must be selected and implemented, together with the control circuitry for managing the antenna height. To bring these elements together, ROS2-based programming is required to handle the navigation logic, inventory scanning, and height control.

Following the set requirements (Table 2) of the project, Robotont has been chosen as the platform to use for creating this project. The justification for this lies in multiple reasons: Robotont is an open-source project already used in numerous educational projects, and it is being made in collaboration with the University of Tartu. An additional advantage of using Robotont is its straightforward way of connecting external devices, which simplifies the integration of other devices required for this project.

3.1 Electronics

For the electronics part of the project, two parts have to be connected to the Robotont- the RFID system and the motor. For the RFID system, a UHF RFID reader module together with an antenna is used, while for the height adjustment system, a motor is needed. A simple representation of the implemented connectivity of the system can be seen in Figure 8 [49, 50].

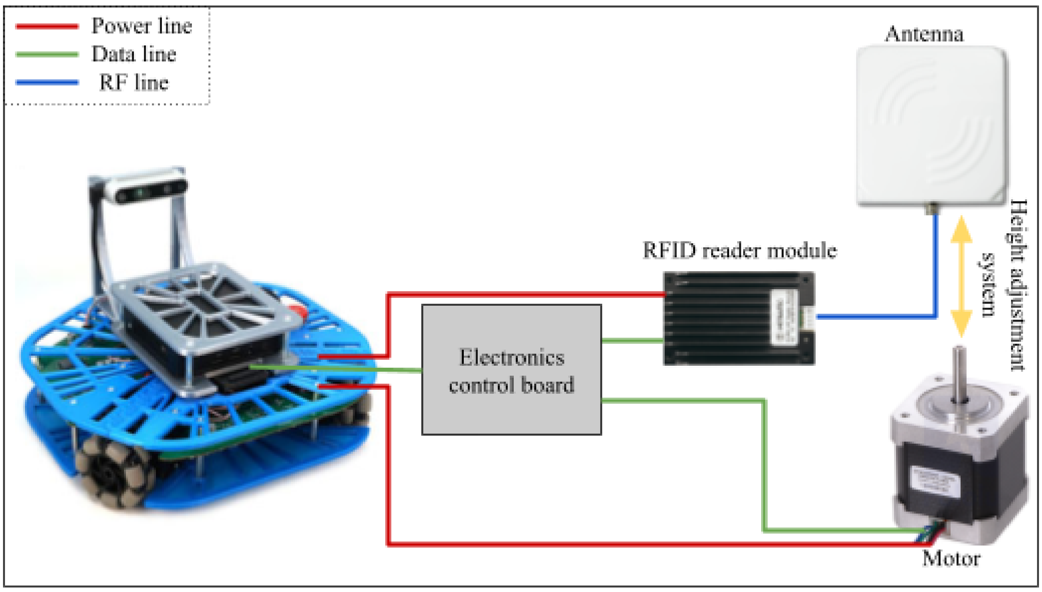


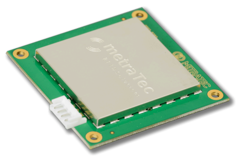
Figure 8: Simple representation of integration of different parts

3.1.1 RFID System

The University of Tartu library already has an implemented RFID tag system that is being used for inventory. These tags are “COMEX – FREYA R6 Al” [51], which are EPC Class 1 Gen 2 compliant, ISO/IEC 18000-6C (ISO/IEC 18000-63). This entails that they communicate at an 860 MHz to 960 MHz frequency, meaning they are UHF RFID tags. Currently, the “Chainway C72 Mobile Data Terminal RFID handheld scanner” [52] is used to perform the tag reading.

The requirement for the new RFID system is that it is compatible with the tags currently used in the UT Library. Also, the reading range has to be long enough to reach the tags, and it has to work even if the antenna is located perpendicular to the books. For this project, multiple options were considered and tested (Table 3).

Table 3: Comparison between different RFID systems

RFID reader	**QRG2 UHF RFID Embedded Module**	**PLRM UHF RFID Reader/Writer OEM Module**	**JT-2540 TM200 UHF RFID 4-port Module**	**Chainway C72**
Abbrevation	QRG2	PLRM	JT	C72
Image				
Range (m)	*0.3*	*12*	*7*	*26*
Output (dBm)	*0 – 9*	*0 – 33*	*13-33*	*30*
Price (€)	*100*	*366*	*58*	*675*
Antenna options	*Inbuilt antenna*	*4 antenna ports*	*4 antenna ports*	*Inbuilt antenna*
Reference	[53]	[54]	[55]	[52]

As shown, the commercially available RFID systems come with different parameters that need to be considered. The most important factor to consider is that the RFID reader has to have enough power to reach tags located up to approximately half a meter away. Additionally, price and integration possibilities also have to be taken into account.

The QRG2, PLRM and JT modules were tested, as it was decided that the C72 ready-made solution is not suitable for integration into a new robotics system. The reason for this is that since it is a handheld device, it is bulky and impractical to implement. In addition, it has an internal battery that could not be easily integrated into the Robotonts power system. Testing the PLRM and JT revealed that the theoretical reading range is higher by a magnitude compared to the one achieved in a real-life, imperfect scenario.

First, the QRG2 reader module was tested. A great feature of this module is the compact size (6 by 6 cm) and built-in antenna, which makes the reader module easy to implement. However, the module was deemed not to be suitable for this project, as it could achieve the 0.3 m range only if the tag was not covered by book covers and was held parallel to the inbuilt antenna. If the book was located perpendicular (as it is in the library) to the reader, the module in nearly all cases failed to read the ID tag.

The PLRM and JT modules both have four antenna ports and were tested using the same antenna - Echo-6P UHF RFID Antenna [56]. The antenna is made for use in Europe and designed for the standard frequency of 868 MHz. It has a gain of 6.5 dBic, meaning that the signal is moderately concentrated, and the size of the antenna is 10 by 10 cm, making it comparably compact. The QRG2 showed satisfactory performance as it was able to detect the RFID tags located multiple meters away, with the books being perpendicular to the antenna. The JT module was not as successful as the PLRM, however, it still had a good enough detection capability to be used for prototyping purposes.

Implementation-wise, connecting the JT module to the Robotont was straightforward, as it already has a USB attached to the UART converter. The QRG2 and PLRM modules required using an additional USB/UART FT232 converter [57]. For the functioning of these modules, 5V and 2A are needed. The USB connection can provide 5V, however, not enough amperage is given. To solve this, power is taken from Robotont's on-board 5V DC-DC converter, providing up to 3A [58].

Although initial testing with PLRM gave more promising results and had a better detection rate, the module's power management IC stopped functioning and had to be sent for repair. Therefore, it was decided to proceed with the JT module as a replacement for the final testing.

3.1.2 Motor

Another part that needs to be connected to the Robotont is a motor that will be used in the height adjustment system. A stepper motor was chosen to ensure high precision and enough torque. The type of chosen stepper motor must provide enough torque to perform the height adjustment.

For this project, the JLB stepper motor model 17HS1538-P4170 [59] was chosen. It is a standard NEMA 17 stepper motor[60] with a step angle of 1.8 degrees. This means that to perform one full rotation, 200 ($\frac{360}{1.8} = 200$) steps are needed. For the control of the motor A4988 driver [61] is used, connected to Arduino Nano [62]. Similarly to the RFID system, the power for the motor is taken from the Robotont.

3.1.3 Integration

A standard practice of using a perfboard (perforated prototyping PCB) is used to connect the RFID system and the stepper motor to the host. Figure 9 shows the connection schematic for PLRM and a stepper motor. The 5 V and 12 V are taken from the Robotonts power supply. Figure 10 shows the real-life perfboard. While this solution is enough for this stage of prototyping, a dedicated PCB should be used in the future.

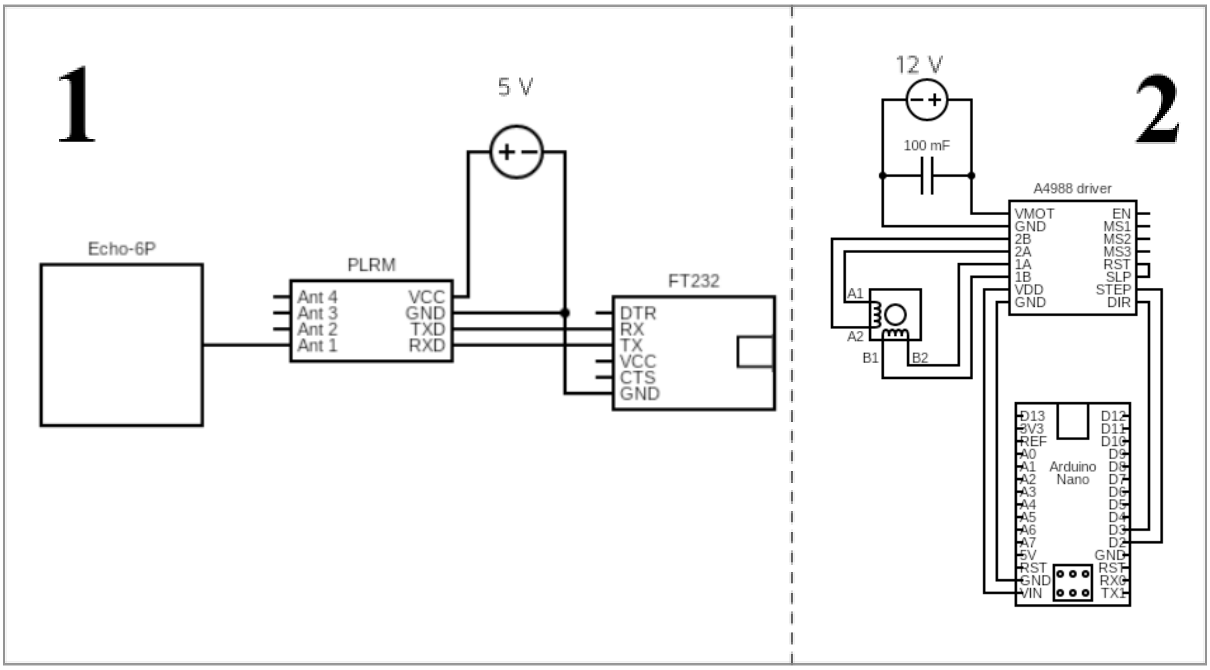


Figure 9: Perfboard schematic for powering the PLRM and stepper motor. 1-RFID system using an external power source and a USB/UART converter; 2- Stepper motor, driver, Arduino Nano connections

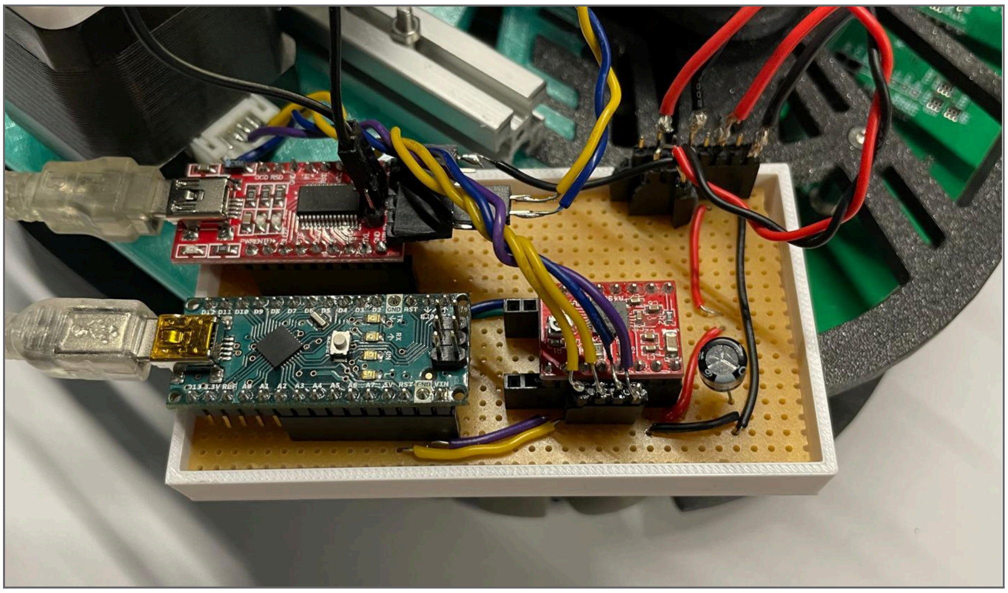


Figure 10: Created perfboard for communicating with and powering the RFID system and stepper motor

3.2 Mechanics

When the electronics have been set up, there is a need to securely attach them to the Robotont and implement the antenna height adjustment system. A full list of all the needed items for building the whole system can be found in the Appendix 2.

3.2.1 Manufacturing New Parts

To accommodate the new design, several new components had to be developed. This was achieved using a combination of additive manufacturing, aluminium profiles, and existing parts. In some cases, components from the original Robotont model were modified to ensure compatibility with the new system, while in others, entirely new parts were designed from scratch. Table 4 describes the parts made using additive manufacturing and their significance for the project, while in Figure 11, the full CAD assembly can be seen. Parts were mainly made using PLA or PETG, depending on their purpose and required strength/flexibility.

3.2.2 Height Adjustment Mechanism

For the robot to be able to determine the book's location precisely, it is important that the antenna emitting the radio waves is located on the same level as the books. For this, a mechanism that controls the height of the antenna is implemented. The mechanism is using aluminium profile construction and a stepper motor that is attached to a 1m long M4 screw with a pitch of 0.7 mm. On the lead screw, there is part no. 2 (Table 4), that connects the antenna, screw, and profile. The system works by the stepper motor spinning the screw, which in turn spins inside the threaded insert. However, since the nut is connected to the profile, it can not rotate around the screw, and instead it can move only vertically, going up or down depending on the rotation direction. An illustrative demonstration of this working principle can be seen in Figure 11.

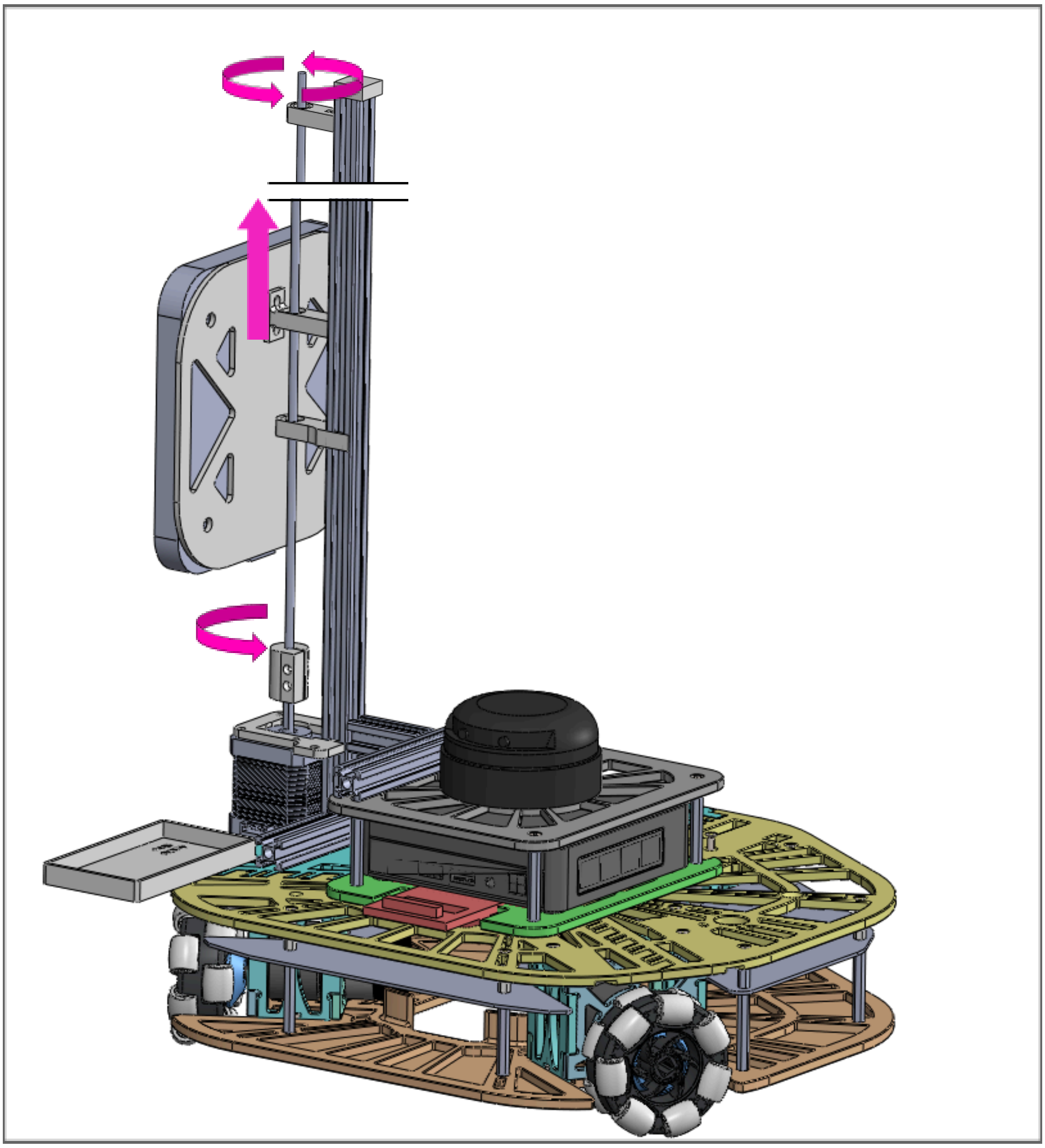
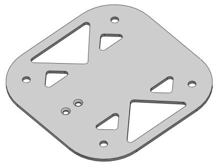
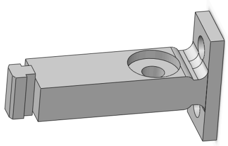
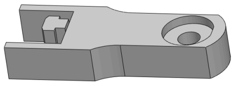
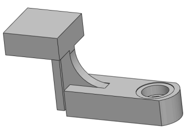
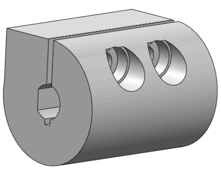
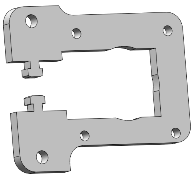
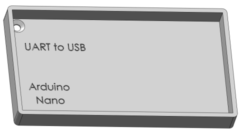
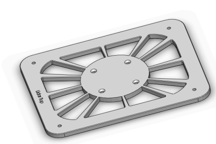
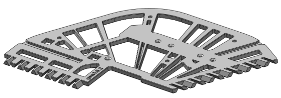


Figure 11: CAD model of the robot with a shown antenna height adjustment logic

Table 4: Produced parts using additive manufacturing

No.	Image	Note
1		Piece for connecting the antenna to the part no. 2. This design was chosen to optimize a lower weight while keeping the tensile strength of the part.
2		Connector between the antenna and the aluminium profile. Slides in the aluminium profile shaft. After manufacturing an M4 threaded insert is added, to ensure the movement on the screw.
3		Stabilizer that connects the aluminium profile and the screw. Required to make the movement smoother and make up for any bends in the screw.
4		Top connector of the profile to the screw. Works using a click-on mechanism and has a M5 bearing, to allow rotation of the screw while stabilizing the movements of it.
5		M5 to M4 coupler for connecting Stepper motor and the screw. M3 threaded inserts are added for durability and strength.
6		A stepper motor holder that functions by being slid on the main aluminium profile and attached to both the stepper motor and another profile.
7		PCB holder box that can be attached to the main chassis plate and has markings for placing the PCB in the correct direction.
8	 	Modified parts from the original robot model to accommodate the attachment of lidar and aluminium profile construction.

3.3 Software

In this thesis, ROS2 was used to program the robot. Some of the used parts, such as the Robotont itself and lidar, had built-in ROS2 compatibility, meaning that it was straightforward to connect them and use the built-in nodes. Other components, however, such as the RFID reader or stepper motor, do not have built-in ROS2 compatibility.

The main goal of the robot is to be able to navigate a set path, scan the RFID tags and determine where and at what height/shelf each book is located. To do this, navigation logic has to be implemented, and simultaneous answers to three questions are needed:

1. What RFID tags are detected?
2. Where is the robot located on the map?
3. How high is the antenna?

The full overview of the main nodes created to achieve this can be seen in Figure 12. Mainly, the nodes and the respective topics that they publish/subscribe to are shown, however, there are other components as well. For example, the navigate_to_pose action server is a part of the NAV2 stack, and in the diagram, it is shown in a simplified way. Or the tag_medians.txt is the text file containing the final output of the system that can be used to visualise the tag location afterwards.

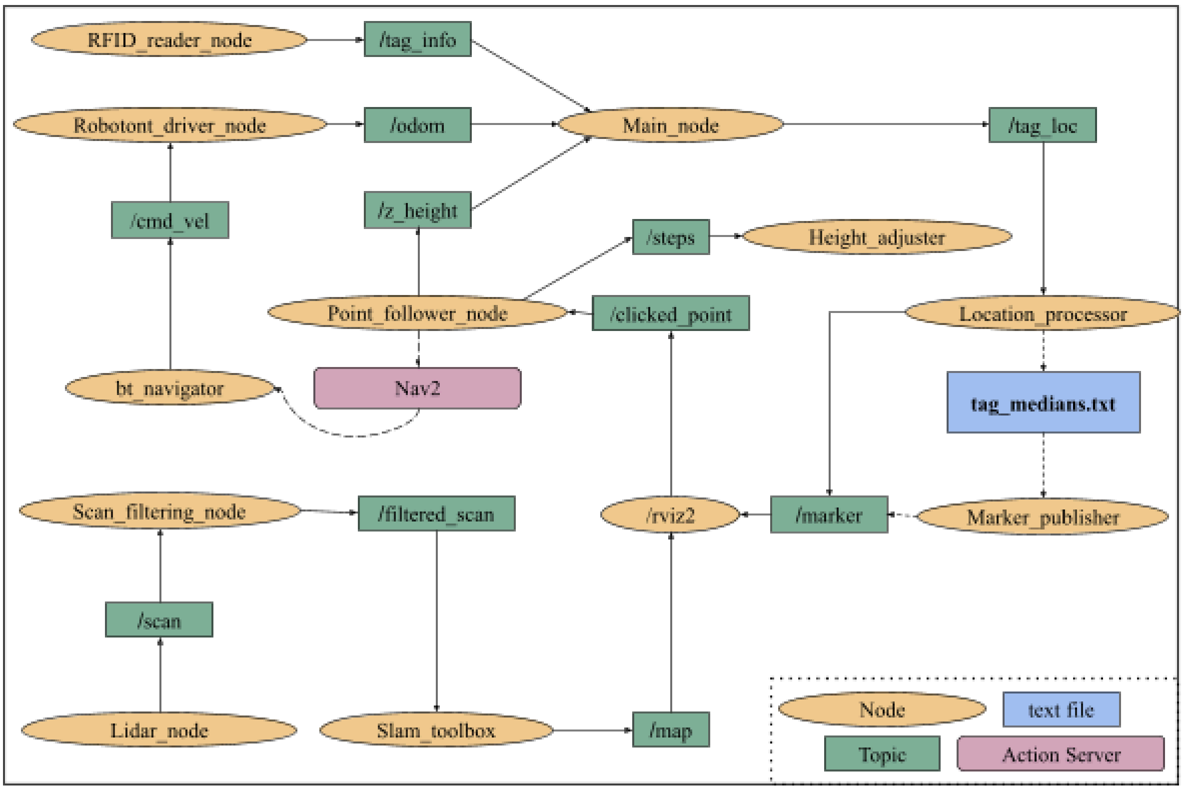


Figure 12: Full overview of the created ROS2 logic

3.3.1 RFID tag detection logic

To perform an inventory assessment, it is necessary to perform RFID tag reading. To do this, communication between the RFID reader module and the host (Robotont) must be implemented. The logic for communicating with two RFID reader modules (JT-2540 and PLRM UHF RFID modules) was implemented.

The PLRM module uses the AT command protocol [63]. The rfid_reader_node establishes communication with the module through a serial port. Then, messages AT+ANT=1 and AT+PWR=27,0,0,0 are sent to the device. These messages specify to use one antenna, and the power for it should be set to 27 dBm. After configuration, every 0.1 seconds, the message AT+INT is sent to detect the RFID tags. The received tags are stored in a list, and after 10 reads have been performed (1 second has passed), the list as a string is published to the /tag_info topic. This kind of logic is chosen as it provides enough precision, but does not take up too much processing power, as a more frequent detection would.

The JT-2540 uses a type of serial communication over an RS232 interface [64]. The working principle is similar- detect the tags every 0.1 second and publish the string to the topic every 1 second. The difference comes in the communication type- messages in the form of bytes are sent to the module. For example, 43 4D 02 02 02 00 00 00 00 starts the reading. After receiving the answer, it is in the shape of bytes as well, meaning that it has to be transformed into the tag ID that is detected.

Here, the hardware-agnostic design of ROS2 appears clearly, as it is possible to test different modules without having to change the system as a whole. Instead, editing just the rfid_reader_node is enough, as no matter what happens in the code itself, the topic /tag_info will receive the same message.

3.3.2 Mapping and navigation

To enable autonomous navigation, the robot must know its position on the map and be able to receive commands in the form of target coordinates. This process involves several main components, each requiring either a dedicated node or a launch file to be executed.

Firstly, a map needs to be created. For this purpose, the Slamtec RPLidar A3 is used [65]. The lidar has an inbuilt ROS2 node that publishes the scanned points on the /scan topic. To transform these data points into a comprehensive map, a ROS tool, Slam (simultaneous localisation and mapping) toolbox, is used. To be able to use it, a transform needs to be introduced to the transform tree so the system knows where the lidar is with respect to the robot. The transform is done between the base_link and laser frames, and the offset in the z-axis is 0.15m to define that the lidar is working on top of the robot, while the roll element of the rotation is set to π radians, so that the map is created correctly (Figure 14.1).

After the transform is done, a filtering of the received data needs to be performed. This is required because the height adjustment system involves using an aluminium profile that is always in the scanned area of the lidar, which ruins the created map. A box filter [66] from the laser filters package is used. It works by defining minimum and maximum x, y, and z coordinates to exclude from the scanned data. Since this is a 2D lidar, the created filter can also be 2-dimensional, only defining the box in the x and y axis. To start the mapping together with the needed transforms and slam toolbox, a mapping launch file has to be executed. Then, using generic keyboard teleoperation [67], the robot has to be guided through the area that needs to be mapped. Once a satisfactory map has been created, it can be saved from RViz2 [68] using the slam toolbox plugin.

Next, the navigation launch file starts RViz2 with an uploaded map made in the previous step. It also starts the lidar node along with the base link to laser transform for localisation purposes, and the main node, which starts the other nodes (Height_adjuster, RFID_reader_node, Location_processor). The point follower node is started too, to guide the driving process. After the robot is given its initial pose, the driving can begin.

The driving logic is as shown in Figure 14.2. It works by clicking on 4 points in RViz2 alongside the shelf (Figure 14.1), which publishes the coordinates of the points on the clicked_point topic. The point_follower_node is subscribing to this topic and collects all the point coordinates in a list. It then sends these coordinates one by one with certain intervals to the Navigate_to_pose action server, which, using Nav2, creates a path to this point and sends cmd_vel commands to the robot for navigating to the point.

The robot starts its way with the antenna extended to its full length. Once the first point is reached, the robot stops for 3 seconds and then continues on in the same driving-stopping pattern until reaching the 4th point. Then, the robot returns to the first point and waits while the antenna is lowered to the height of the 2nd shelf and sets the appropriate Z for calculations. After it is done, it follows again along the 4 points, the same as before. This logic (Figure 13) ensures that the robot drives close to the bookshelf and the inventory is done with set precision.

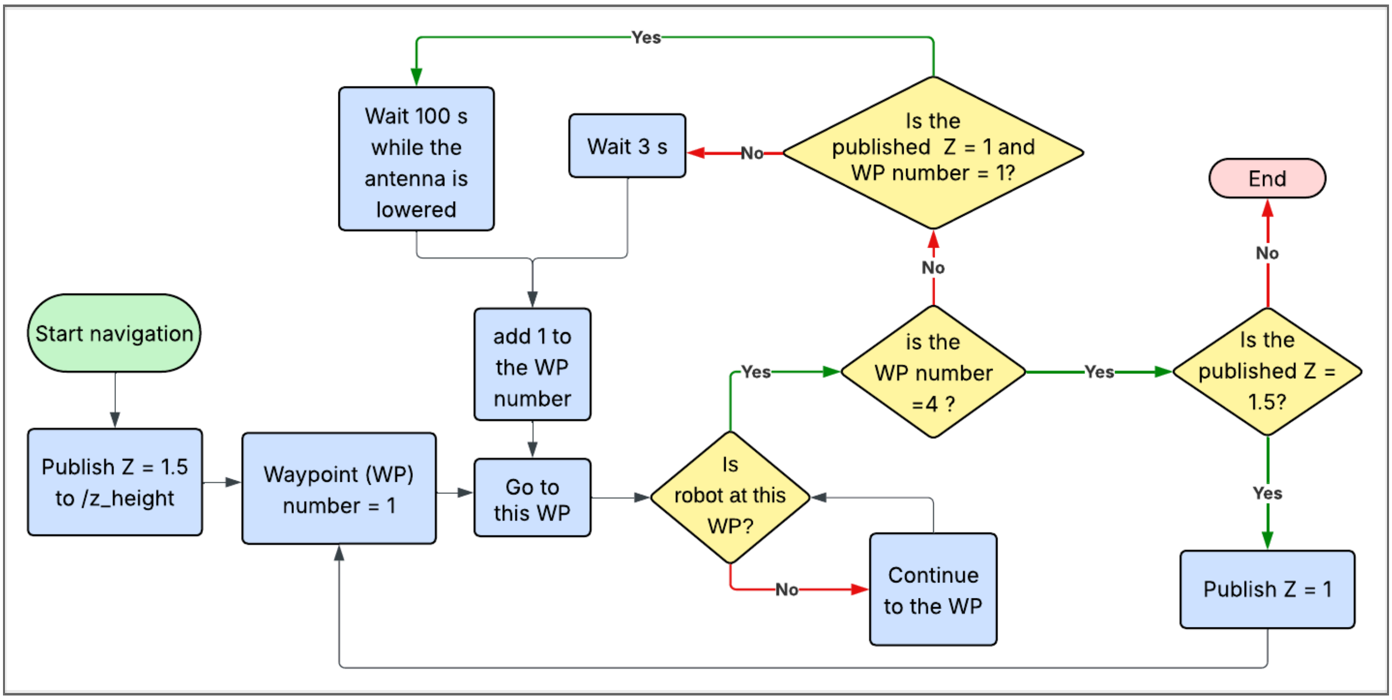


Figure 13: Unified Modeling Language (UML) diagram of the navigation and height adjusting logic

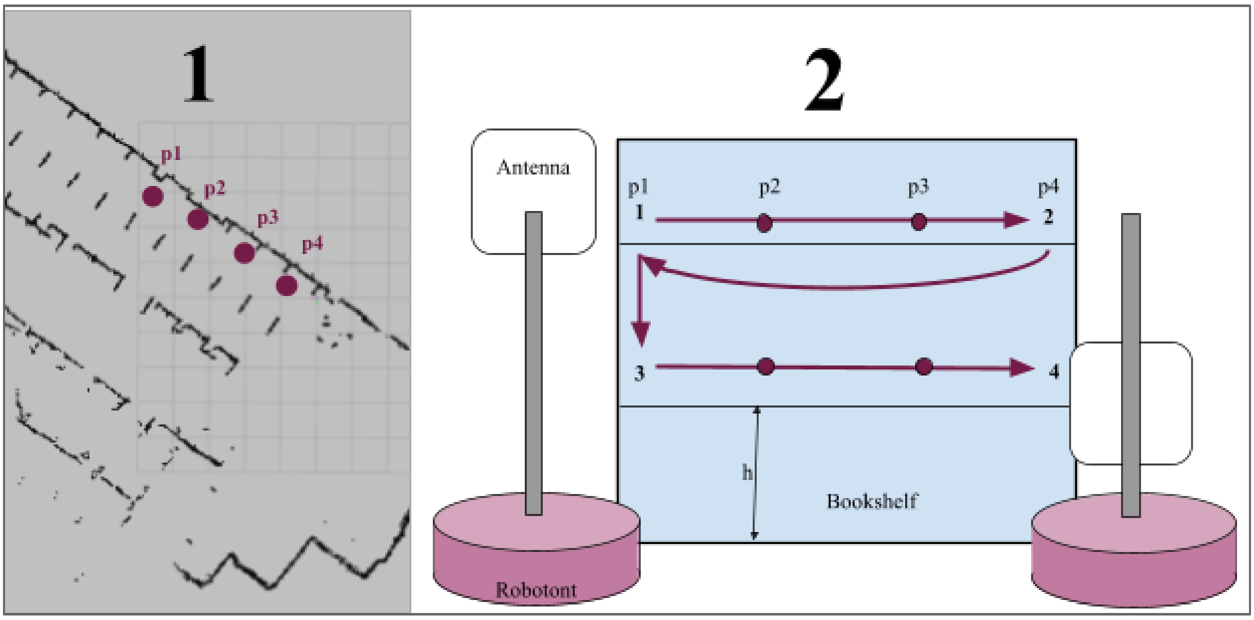


Figure 14: 1- A map of a part of the University of Tartu library halls, visualised in RViz2 with 4 given navigation points; 2- Driving logic between 4 given points. Robotont starts with an extended antenna and scans the higher shelf following the points. After returning to the first point, the antenna is lowered and waypoint following repeated.

3.3.3 Height-determining node

As mentioned in the mapping and navigation part, the antenna needs to be lowered once it reaches the 1st point again. For this, the point_follower node publishes a message to the /steps topic to physically lower the antenna, and to the /z_height topic, to set the z coordinate for further calculations.

Once the robot has reached the 1st point for the second time, the point_follower node stops the robot in place for 100 seconds and sends a message of "-50000" to the /steps topic to lower the height of the antenna by 17.5 cm - the height of the shelf (Formula 1). The height_adjuster_node is subscribing to the topic. It has created a serial connection with the Arduino Nano on which a stepper motor control code is uploaded. The number that the height adjuster node sends to the Arduino Nano determines the step count, and the positive or negative sign determines the rotation direction.

In addition to the step count, the message about z height is published by the point_follower node every time the 1st point is reached. When reaching the 1st point for the 1st time, a message of 1.5 is published to the z_height topic. When reaching the 1st point for the second time, a message of 1.0 is published to indicate the lower shelf. This is the number that will be taken into account for determining the height of the book.

$$step\ angle = 1.8\ degrees,\ pitch = 0.7mm, h = 175mm, speed = 2\frac{ms}{step}$$

$$\frac{360\ degrees}{1.8\ degrees} = 200\frac{steps}{rev} \quad (1)$$

$$\frac{h}{pitch} = \frac{175\ mm}{0.7\ mm} = 250\ rev \quad (2)$$

$$200\frac{steps}{rev} * 250\ rev = 50000\ steps \quad (3)$$

$$\frac{1step}{0.002\ second} = 500\ steps/\ second \quad (4)$$

$$\frac{50000\ steps}{500\frac{steps}{secons}} = 100\ seconds \quad (5)$$

Formula 1. Calculation of the step count and time taken to lower the height of the antenna by one shelf

3.3.4 Tag Location Processing

The main node is subscribing to the previously described /odom, /tag_info, and /z_height topics. It combines all of these parameters together in a string and publishes it to the topic /tag_loc. Now, the tag localisation node subscribes to this topic and keeps track of each tag to estimate the most probable location, as well as to create a heatmap.

The logic works by creating a dictionary and, whenever a new tag appears in the /tag_loc, placing the tag as the key and the coordinates as values. Whenever a tag appears repeatedly (as it is detected from another location, with different odom and/or z height values), its new coordinates are added to the dictionary. Every 5 seconds, the median calculation function is called to find the median value from all the detected x, y, and z coordinates for each tag individually. Additionally, the function identifies and keeps track of the positions that are farthest from the median in the x and y coordinates. This information can later be used to generate a heatmap, illustrating the full range of locations where each tag has been detected.

When this is done, the function writes each tag ID with its respective median coordinates and the furthest x and y points to a tag_medians text file (Figure 15). For the Z coordinate, the furthest point is not tracked, as later, when visualising the heatmap, a 2D representation is clearer. Additionally, z height can only be the value that is sent to the /z_height topic. This entails that if there are, for example, three shelves, then the z coordinate can only have three possible values, meaning it will not fluctuate as much as the x and y values.

In addition to writing the coordinates in the text file for the later tag look-up option, the localisation node also publishes the marker information for the topic /marker, enabling real-time visualisation on the map to verify that the detection is working correctly.

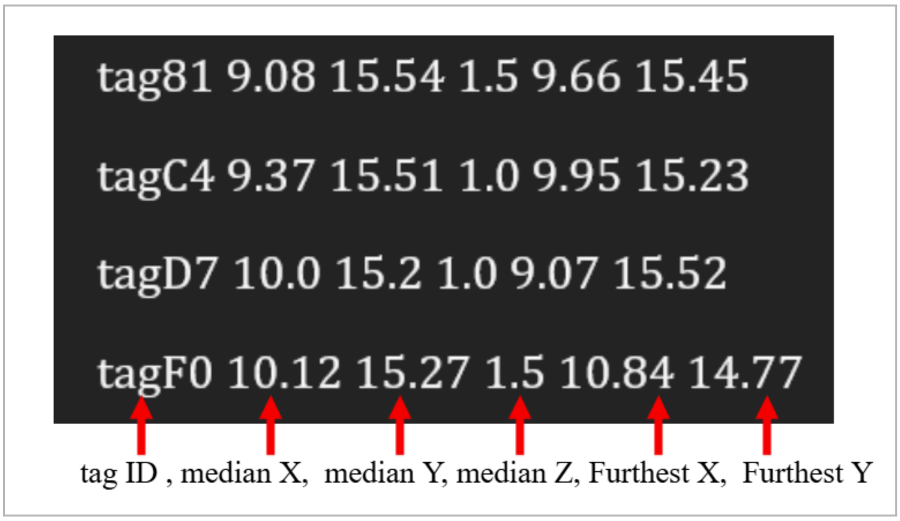


Figure 15: Example of tag localisation node output- tag_medians.txt

4 RESULTS AND DISCUSSION

For a better assessment of the work, the achieved result can be compared (Table 5) to the requirements given for this project.

Table 5: Achieved result comparison with the requirements

Nr.	Requirement	Level of fulfilment
1	UHF RFID system.	The chosen RFID system uses JT-2540 TM200 UHF RFID 4-port Module together with the Echo-6p UHF RFID antenna, meaning that the system is perfectly compatible with the current tags used in the UT library, and it follows the European RF communication protocols.
2	Adjustable antenna height	The antenna height can be adjusted up to one meter. Using a higher construction would create a risk of the robot falling over and damaging other parts. Thinking of a safe solution for reaching the higher (2 m) shelves can be considered for future work.
3	ROS2 compatibility	The created software is fully based on ROS2 Jazzy.
4	Autonomity	After receiving the map and points to follow, the created solution is capable of independently following the points, with the needed time intervals, and adjusting the height of the antenna as specified.
5	Open source	All the created code can be found on GitHub (Appendix 1) alongside the CAD files and instructions for setting up and using the system.
6	Reliable output of the book's height and location	If the book is detected, its location will be showcased within the heatmap; however, at times, the books are not detected due to inconvenient placement or insufficient strength of the antenna. The height detection tends to be correct, however, there are edge cases where the shelf is determined incorrectly, for example, if at any point the robot is located further away from the shelf, the area that the antenna detects is larger.

Multiple test runs were performed to test the system's accuracy. The first and simplest one was done with a static antenna height close to the ground, where the books were placed (Figure 16.1). This test involved using the PLRM reader module. It provided satisfactory results, as all the books were detected and, in reality, they were within the shown heatmap. The issue evident in this test run is that since the antenna strength was high, the results were not as precise as one could wish for, and, in a situation with an abundance of books, it might get difficult to localise the desired book.

Test runs 2 (Figure 16.2) and 3 (Figure 16.3) differed in the book placement and navigation logic, and also used the JT reader module instead of the PLRM. It must be mentioned that at some points, the robot had to turn, and doing so resulted in the detection of books that are located on other shelves; however, since this is a test run meant for just one shelf, the detected tags were removed from the list.

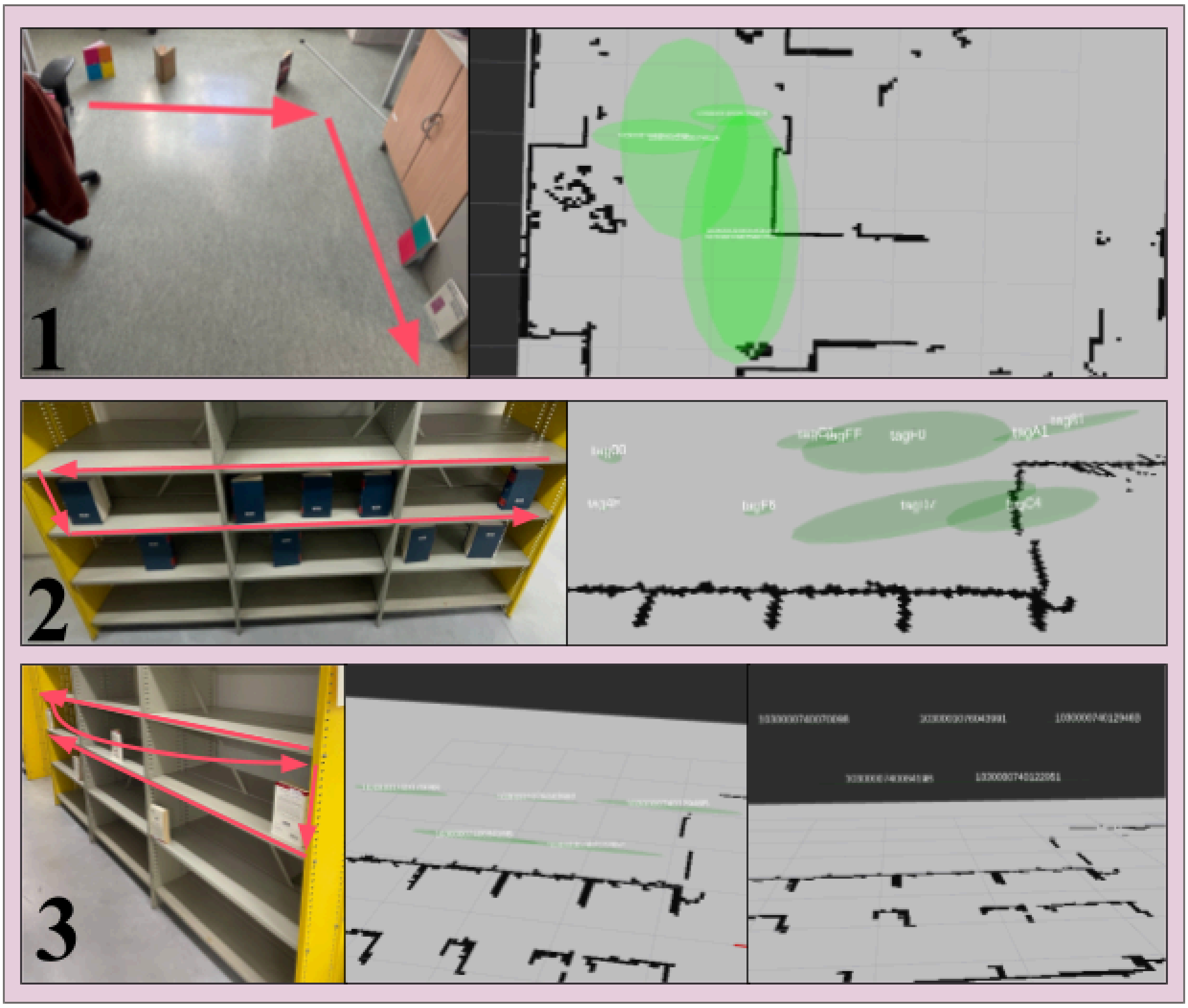


Figure 16: 1- test in 2D space with a static antenna height and PLRM; 2- 3D test run with JT; 3- 3D test run utilising the principle of navigation described in section 4.3.2 with JT

The second run showed success in determining the shelf height, however, the coordinates were inaccurate due to the problematic navigation pattern of the robot.

The third run showed the most success and can be used a proof of concept for this project. The five books placed on the shelves were correctly located together with their respective shelf height. In addition, the heatmap sizes were reasonable and much more concise compared to the 1st test run.

When testing the robot in a real-life scenario of driving alongside a fully stacked shelf, not all the books were detected. This is due to the JT RFID module not being powerful enough to detect books that are not placed in the correct orientation, have thick covers or are moved deeper into the shelf. This implies that even though the first test run had larger heatmaps and the 2nd and 3rd showed more precise detection, for real application of this system, the PLRM would be better suited. This is because the PLRM will detect more books with less precision than the JT, which misses some books but detects others with more precise locations.

Figure 17 shows the fully assembled robot.

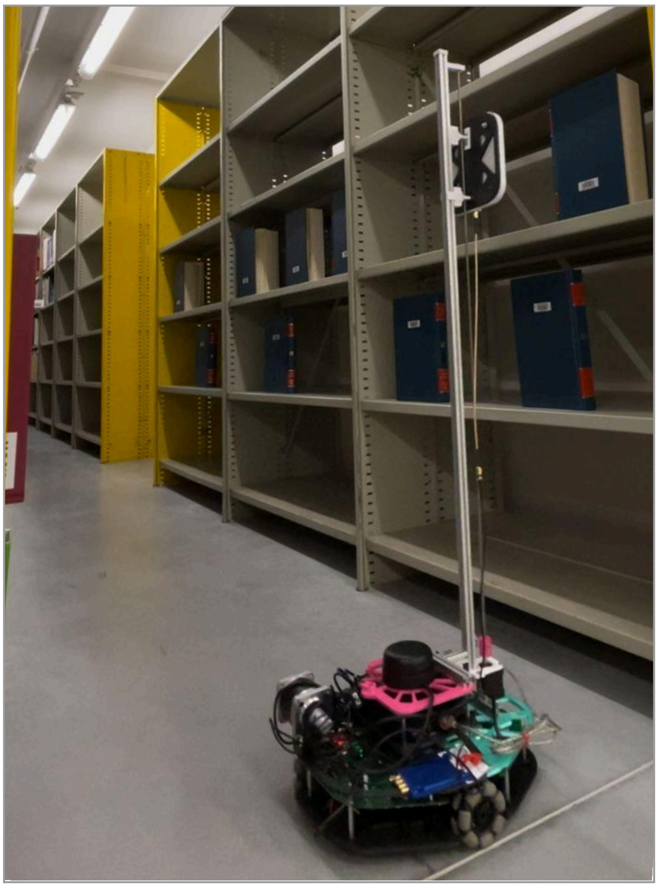


Figure 17: Fully assembled robot performing 2nd test run

4.1 Future Improvements

There are improvements (Table 6) that should be done in the future to transform this solution from a prototype to a fully working autonomous inventory management robot.

Table 6: Future improvements of the system

Nr.	Future work	Description
1	Improved tag detection	As mentioned, the currently used JT does not detect tags well enough. This could be solved by fixing and implementing the PLRM again or choosing another high-power reader module.
2	Higher pitch and different type of the lead screw	The current pitch of the lead screw is 0.7 mm, resulting in the time needed to lower the height being 100 s. A higher pitch, for example, 4 mm, would bring this time down to 17 s, improving the overall speed of inventory.
3	Cable management	Currently, the cable connecting the antenna and reader module is not constrained. With the antenna being extended, it is firmly stretched; however, when the antenna is lower to the ground, the cable is loose and can get in the way of the lidar or fall under the wheels. Either 3d-printed or commercially available bendable cable holders could be used to solve this.
4	Fixed navigation	At times, the robot makes unwanted turns while navigating; constraints could be set for the navigation process to fix this. For example, the robot could only move in a straight line when scanning a shelf, ensuring that no rotation is done and the antenna is always facing the same side.
5	Increased detection height	The shelves in the library are 2 m high. Currently, the book detection can reach 1 m. Using another robotic platform with a bigger weight, using a lighter antenna or adding helper wheels to the Robotont could make the 2m detection possible. While keeping the current setup, the best option would be to implement a rotation mechanism for the antenna, so that when it reaches a height of 1 m, it starts changing its angle to be oriented towards the top shelves.

SUMMARY

Proper inventory management is essential for the functioning of different venues, including libraries. The University of Tartu library currently uses a manual inventory management system that involves librarians scanning all the tag IDS by hand, which, in ideal conditions, takes approximately 54 days for one inventory round. A solution to automate this process has been attempted.

The created system consists of an open-source robotic platform Robotont, a UHF RFID system composed of a JT reader module and Echo-6P antenna, as well as a height adjustment system involving aluminium profiles, lead screw, and a stepper motor. To combine these parts, mechanics, electronics and software development had to be done.

The created solution shows promising results in the test runs. It is capable of creating a map and afterwards using it to navigate in a given pattern, while detecting the books and switching the height of the antenna as required. The detected data can be displayed either in real time or afterwards from a text file that has combined all the book ID's with their respective location. Although the current detection accuracy falls short of fully replacing the manual process, this limitation could be addressed by upgrading to a more powerful RFID reader module.

To summarise, this thesis presents a functional prototype for an autonomous library inventory management system. It explores various design choices and RFID configurations, and successfully integrates all key components into a working system. While the solution is not yet ready for full deployment, it provides a solid foundation for future work and serves as a proof of concept for continued development in this area.

ACKNOWLEDGMENTS

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I thank the University of Tartu Library personnel for their idea of this thesis and for their kind support in providing help for testing in the library halls.

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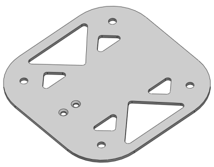
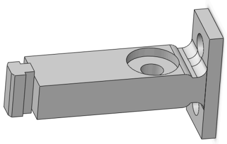
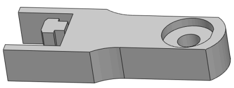
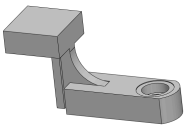
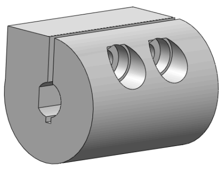
APPENDIX

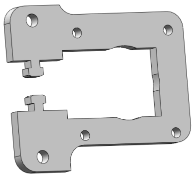
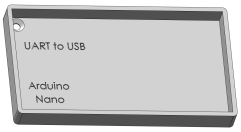
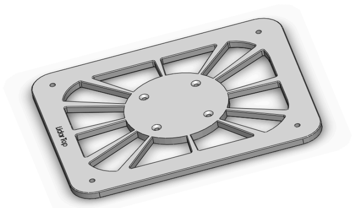
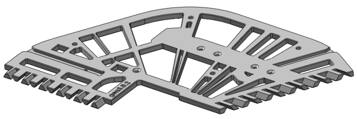
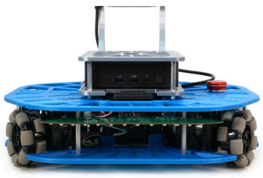
1. Ut-ims-robotics GitHub repository

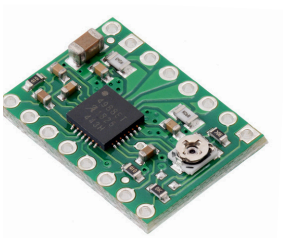
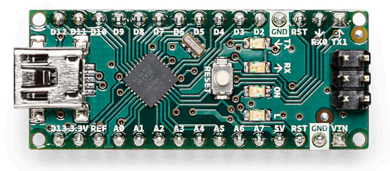
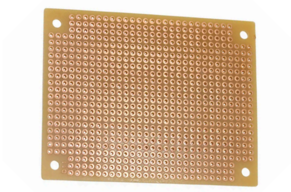
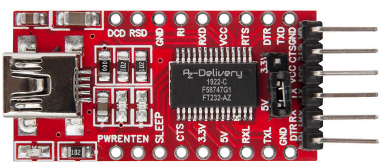
link to the GitHub repository:
https://github.com/ut-ims-robotics/zvirgzdina-thesis-2025-robotont-inventory

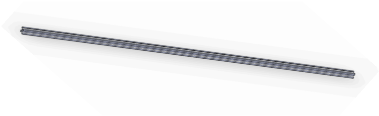
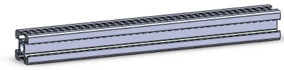
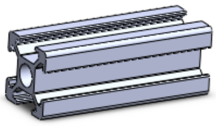
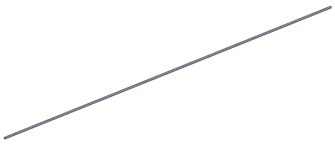
2. Bill of materials table

Bill of materials table. In addition to the mentioned components, M3 and M4 screws are used.

Nr.	Image	Description	Quantity
1		Antenna connector	1x
2		Antenna to lead screw to profile connector	1x
3		Profile to lead screw connector	1x
4		Top holder	1x
5		4 mm to 5 mm coupling	1x

6		Motor holder	1x
7		PCB box	1x
8		Lidar connector	1x
9		Main chassis plate	1x
10		Gen 3 Robotont	1x
11		SLAMTEC RPLIDAR A3	1x
12		Metratec Echo-6P antenna	1x
13		JT-2540 TM200 UHF RFID 4-port Module	1x

14		1 m long SMA to TNC cable [70].	1 x
15		JLB stepper motor model 17HS1538-P4170 [71]	1x
16		A4988 stepper motor driver [72]	1x
17		Arduino Nano [73]	1x
18		Perfboard [74]	1x
19		FT232 converter [75].	1x

20		USB to USB mini cable [76]	2x
21		Alluminium profile 15x15x1000 mm	1x
22		Alluminium profile 15x15x140 mm	2x
23		Alluminium profile 15x15x40 mm	1x
24		Lead screw, M4, 100 cm	1x
25		M4 bearing [77].	1x
26		M4 threaded insert [78].	2x
27		M3 threaded insert	2x

Bill of materials (BOM) table

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