Robotized Warehouse for the Robotics Engineering Teaching Laboratories

by

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Abstract

The goal of this project is to develop a robotized warehouse for the Robotics Engineering teaching laboratories at WPI. Robotics Engineering (RBE) students at Worcester Polytechnic Institute frequently borrow hardware components from one of the teaching laboratories for their projects and coursework. Components are typically ready for pick up in a matter of hours, but in some circumstances, wait times can be up to two days - especially around the end of a term, when the volume of requests reaches a peak. Component requests are currently fulfilled manually by a laboratory assistant, which limits the number of requests that can be fulfilled during peak demand. One way to obviate this problem would be to increase laboratory staffing during peak hours, but this is currently not possible due to the requirement to de-intensify spaces on campus to effectively combat the spread of Coronavirus. We propose an automated warehouse where component requests are fulfilled by a robot. Our solution promises to offer higher bandwidth than the current procurement system based on manual fulfillment. To prove the concept of our system, a small-scale version of the warehouse was built, consisting of shelves with six different bins with components that represent the variety of items that students typically request. Using a graphical user interface on a computer, a student selects the component(s) he or she wants to collect, and the robot automatically retrieves those components from the warehouse, thereby enabling component retrieval and delivery with minimal human involvement. Besides showing that our proposed solution meets requirements and stakeholder needs, we also discuss the implications that the introduction of robots bears on the staffing of RBE laboratories.

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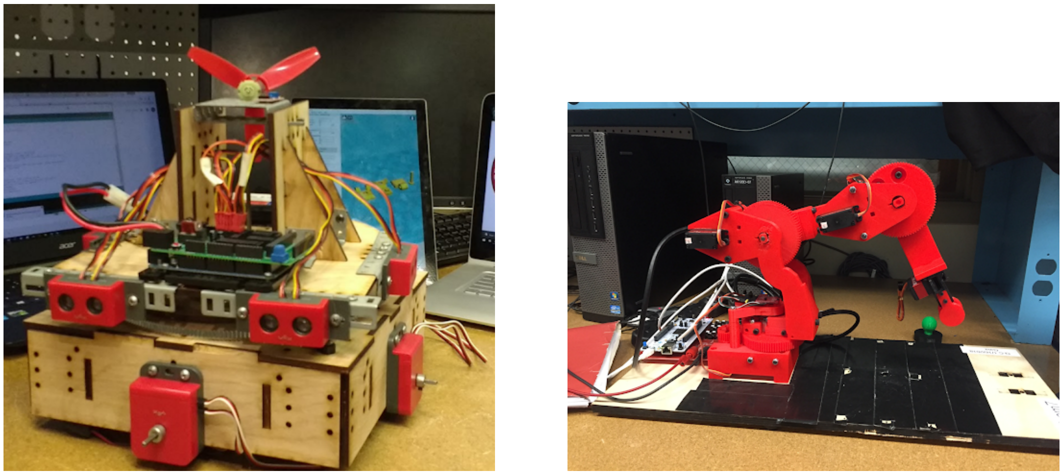
Chapter 1

Introduction

The Robotics Engineering (RBE) department at Worcester Polytechnic Institute (WPI) is home to the nation's first undergraduate robotics program [1]. Offered for the first time in 2007, the curriculum consists of a sequence of seven-week courses that combine theoretical work in the classroom with practical, hands-on assignments that are carried out in a laboratory setting. Throughout both the Undergraduate and the Graduate RBE Programs, students learn how robots work by having the opportunity to build, model, and control actual robotic mechanisms and electronics. Examples of RBE class projects can be seen in Figure 1.1. To complete laboratory assignments, students utilize a variety of hardware components made available to them by the RBE department. Hardware components include motors, microcontrollers, and a variety of sensors. In the remainder of this document, these items shall be referred to as simply *components*.

Components are generally borrowed by a student for the duration of a term and then returned to the department upon completion of the course. Students can request components by placing a reservation on a dedicated, web-based inventory application called Odoo. Requests are reviewed by a member of the RBE laboratory



(a) RBE 2002 robot (b) RBE 3001 robot

Figure 1.1: Example RBE Term Projects

staff and, upon approval, students can go to the laboratory to pick up the requested components. This process requires coordination between the laboratory staff and students. The team surveyed 23 RBE students and found that the current wait time for a request to be completed can be anywhere from a few hours up to a few days. Additionally, meeting in person creates the risk of spreading the coronavirus and other diseases since the student and lab staff are physically close to each other and touching the same components.

The team proposes increasing the automation in the current component request process, allowing students to retrieve components without needing to coordinate with the laboratory staff. The proposed automated system will allow students to borrow the most requested components more easily and quickly compared to the current system the RBE laboratory utilizes. The new system would make receiving these components more convenient for students, reduce the workload for the RBE lab staff, and decrease the risk of the spread of diseases. The proposed system will take the place of the laboratory staff's role in procuring components from the component storage room. The system organizes the hardware components into bins on shelves that are in a grid layout. Lines are drawn on the floor to indicate the rows and columns of a grid and the areas where the storage shelves are placed. A kiosk will be available to students that enables them to select components to be borrowed. A mobile robot, capable of navigating the grid can retrieve these bins from the shelf and bring them to the student. After the student takes their components from the bin, the robot can return the bin to its spot on the shelf.

1.1 COVID-19 Interruption

The entirety of this project took place in the Fall of 2020 when the COVID-19 pandemic had seen a large uptick in cases. This uptick in cases had caused WPI to set certain restrictions on the students to help mitigate the spread as much as possible. Due to these restrictions, the Foisie Robotics Laboratory at WPI prohibited group meetings so the team ceased on-campus meetings entirely before the testing was completed. Since firmware and mechanical work were done concurrently and independently, the team only had three meetings to prototype and test together on campus. The remaining work was completed remotely.

Chapter 2

Background

This chapter introduces the stakeholders of this project and explains the background information necessary for understanding how the RBE department runs the RBE laboratories, as well as the current process for borrowing components from the RBE laboratories.

2.1 Robotics Lab Staff and Operations

RBE students can work on their laboratory-related coursework in the dedicated laboratories available to them on the WPI campus. There are two RBE laboratories, each with its own Lab Manager (LM). The LM is responsible for keeping their laboratory organized, designing the laboratory assignments, and assisting the students with these assignments. The LM needs Lab Assistants (LA) to whom he/she delegates laboratory responsibilities. These LAs are typically students who have taken the RBE laboratory courses and familiar with the needs of the courses. The LAs are responsible for providing components necessary for completing laboratory assignments.

2.1.1 Stakeholders

The stakeholders that were identified for this project are the four Lab Assistants in the RBE Department, the Foisie Robotics Lab Manager, and the undergraduate student body of the RBE department. The stakeholders were surveyed or interviewed to learn more about how the current component procurement system works, about the user experiences with the system, the potential effects an automated system could have on them, and their roles in the current process. The surveys and interview questions can be found in Appendices A and B. Additionally a member of WPI's Coronavirus Emergency Response Team (CERT) was identified as a stakeholder and interviewed to better understand the restrictions they place on the RBE department while operating during the COVID-19 pandemic and how WPI is working to prevent the spread of the virus while classes are in session. These stakeholders are described below and summarized in Table 2.1.

Lab Assistants

Lab Assistants play a direct role in helping students receive components from the RBE laboratories. They are primarily responsible for fulfilling student requests for borrowing and returning robotic components for laboratory assignments.

Lab Managers

The Lab Managers also plays a key role in helping students receive components from the RBE laboratories. LMs manage the inventory of the laboratory components available to students, and oversee the work of the Lab Assistants. The Lab Manager also works with faculty to design laboratory assignments and helps to determine which components are necessary for these assignments.

RBE Students

The undergraduate RBE students use the current process of obtaining components from the RBE laboratories on a daily basis. Students use the laboratories during the course of the seven-week project timelines, so the current system for borrowing components is essential to their ability to complete their projects.

Coronavirus Emergency Response Team (CERT)

CERT aims to keep WPI Students and Faculty safe from illnesses during the COVID-19 pandemic by enacting cleaning and safety measures to reduce the spread of the disease on the WPI campus [2]. Current safety measures in place include mandatory mask-wearing, social distancing when possible, weekly on-campus testing for all students and faculty commuting to campus, as well as areas for students to isolate and quarantine. It is important to implement safety measures in the RBE laboratories as well, as they are part of the WPI campus. However, having students share components that could be contaminated with coronavirus, which can survive for hours or days at a time [3], poses a cause for concern in the current protocols. To reduce the risk of spreading the disease through the sharing of components for projects, the WPI RBE Laboratories have redesigned many course projects and laboratory assignments to be done individually by each student. This requires students to have their own equipment, which is purchased or borrowed from the RBE laboratories.

Table 2.1: Stakeholder Identification

Stakeholder	**Involvement**	**Extent of Involvement**	**Rationale**
RBE Lab Manager (SH01)	Direct, Engaged, Informed, Positive	Decision making authority, as needed meetings, providing resources	Customer of system
RBE Lab Assistant (SH02)	Indirect, Consulted, Not Informed, Positive	Feedback of current system	System replaces some of their tasks
RBE Students (SH03)	Direct, Consulted, Not Informed, Positive	Feedback of current system and prototype testing	Will interact with system as needed
CERT (SH04)	Indirect, Consulted, Not Informed, Neutral	Sanitary regulations and processes at WPI	Power to deny sharing of components

2.1.2 Lab Assistant and Student Survey

A survey hosted on Google Forms was distributed to the four LAs currently working for the RBE department. A different survey was also hosted on Google Forms and distributed to the RBE students via email and the RBE Discord server. Discord is an online messaging service that hosts chat rooms. Students in the RBE program have created chat rooms on this service so that it is easy and convenient for students and faculty to talk about their course work and ask each other questions. The LA survey was used to try to gauge the shortcomings of the current system and how to meet the needs of a system maintainer. See Appendix A for the full list of questions.

Similarly, the student survey is meant to measure the shortcomings of the current system and how to meet the needs of the students by gathering quantifiable data. See Appendix B for the full list of questions.

Additionally, the Foisie RBE Lab Manager and a representative from WPI's COVID Emergency Response Team (CERT) were interviewed. The Lab Manager was asked questions about the current component procurement process and where they see improvement needed, as well as their ideas for an automated solution. The member of CERT was asked questions about COVID-19, how the school handles sanitization, as well as any concerns they have with the current sanitization process. The responses were used to understand the components procurement and return system which is described in the next section.

2.1.3 Student Survey Results

After analyzing the student survey, the team found that half of the surveyed students stated that the procurement process took at least one day, and more than 8% said it took over two days as seen in Figure 2.1. Furthermore, more than half of the surveyed students said that the delay in receiving components hinders their ability to do well on the project as shown in Figure 2.2. Therefore, one technical challenge that the proposed system must accomplish is making sure that the implementation is able to provide components quickly to students so that procuring components is not a limiting factor of their projects and assignments. Some of the respondents surveyed have requested 25 individual components or more all at once, and during peak request times, the Lab Assistants have needed to fulfill student component requests as frequently as four times an hour. The proposed system must keep up with orders during these peak times to prevent delays.

The students were also asked to describe their knowledge of Odoo. This is explained in more detail in the next section. 32% of students surveyed have little or no knowledge of Odoo, or even how to currently get components for robotics projects as shown in Figure 2.3. Others said that Odoo itself was not intuitive. Odoo is currently used to tie students to components, bill students if necessary, as well as send components to students that are remote. The proposed system should be understood without lengthy explanations or tutorials to encourage students to use it.

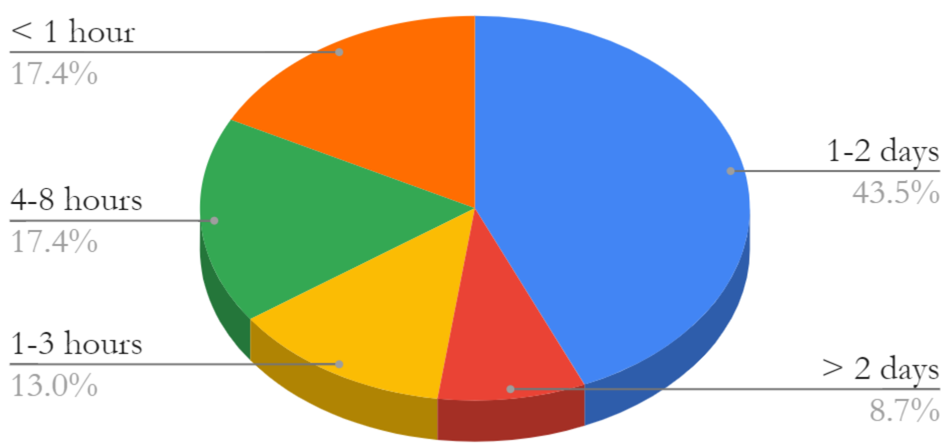


Figure 2.1: "What is the longest time you typically wait to receive the component after requesting it? "

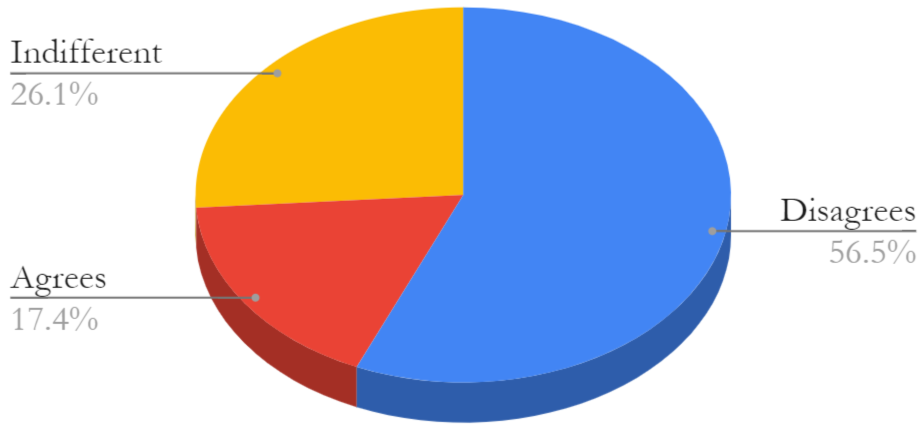


Figure 2.2: "The delay in receiving components does not hinder my ability to do well on the final project."

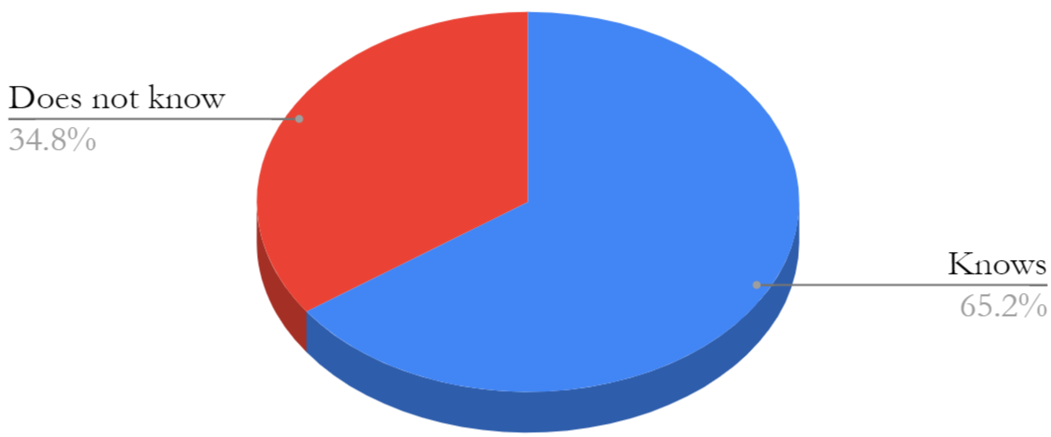


Figure 2.3: "Can you please describe the process you have to follow to request components through ODOO?" simplified responses graphed

2.1.4 Overview of the Current System for Components Procurement and Return

The Lab Assistant Survey and Interviews with the Lab Manager gathered information about the current system for components procurement and return. In the current process, to receive components from WPI's Foisie RBE laboratory, students must place an order through Odoo as seen in Figure 2.4, which is a web application.

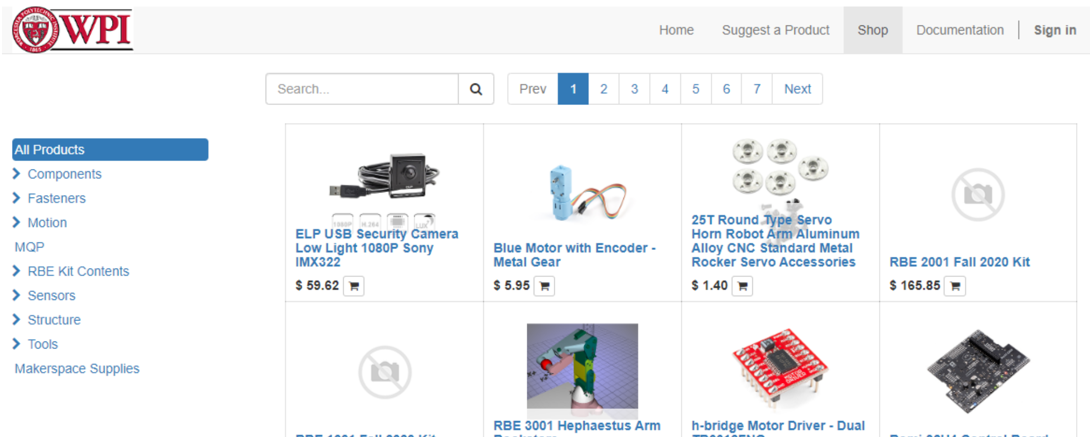


Figure 2.4: Odoo e-Shop webpage

The Foisie RBE laboratory has used Odoo since 2018 to enable students to borrow, purchase, and return laboratory equipment and robotics components. Odoo holds individuals accountable for any components they have broken and allows students the flexibility to either purchase the components they are using or return them once their course is over.

Figure 2.7 represents the current process, where each column consists of all the tasks a specific person or system performs in the current component procurement process. The left-most column follows the actions of the RBE student trying to borrow robotic components, the middle column represents the Odoo "e-shop" from which the students request their robotics components, and the third column follows the actions of the RBE Lab Assistant that is needed to process the order and distribute the components to the student. When an order has been placed on Odoo, the order must be ‘processed’ by an LA, who will source the components from one of the lab offices, and assign them to the student who placed the order. After their order has been processed, the student must coordinate a time to meet with the LA to receive the components which add time constraints given that this process can add up to two days. Students also complain that Odoo is not intuitive to search for components, which makes it difficult to place an order.

In addition to time constraints, safety measures must be addressed in the current climate of the COVID-19 pandemic. The current system for borrowing, purchasing, and returning components to the RBE laboratory increases the chance of spreading the disease due to direct physical contact between laboratory staff and students during the exchange of components. Furthermore, all of the components are located in a cramped and poorly ventilated office. To prevent the spread of diseases, this office space has a maximum occupancy of one, so only one LA can procure components at a time. The office space is shown in Fig. 2.5 and Fig. 2.6.

Figure 2.5: Components Storage Office from Inside View

Figure 2.6: Components Storage Office from Outside View

Currently, upon completion of their project, each student has two options. One option is to purchase the components used to make the robot, allowing them to keep their robot. The other option requires that the robot be disassembled and that components are returned. To make a return, students must find the LA on duty and give the components to them. Upon returning the components, the lab assistant must inspect them, making sure they are not damaged, before placing them in their correct bins in the lab office. Students are not expected to return components that can only be used once, such as tape or zip ties, nor are they expected to return components that have insignificant costs, such as resistors, diodes, and capacitors. These types of components that are not returned will be referred to as consumables in the remainder of this document.

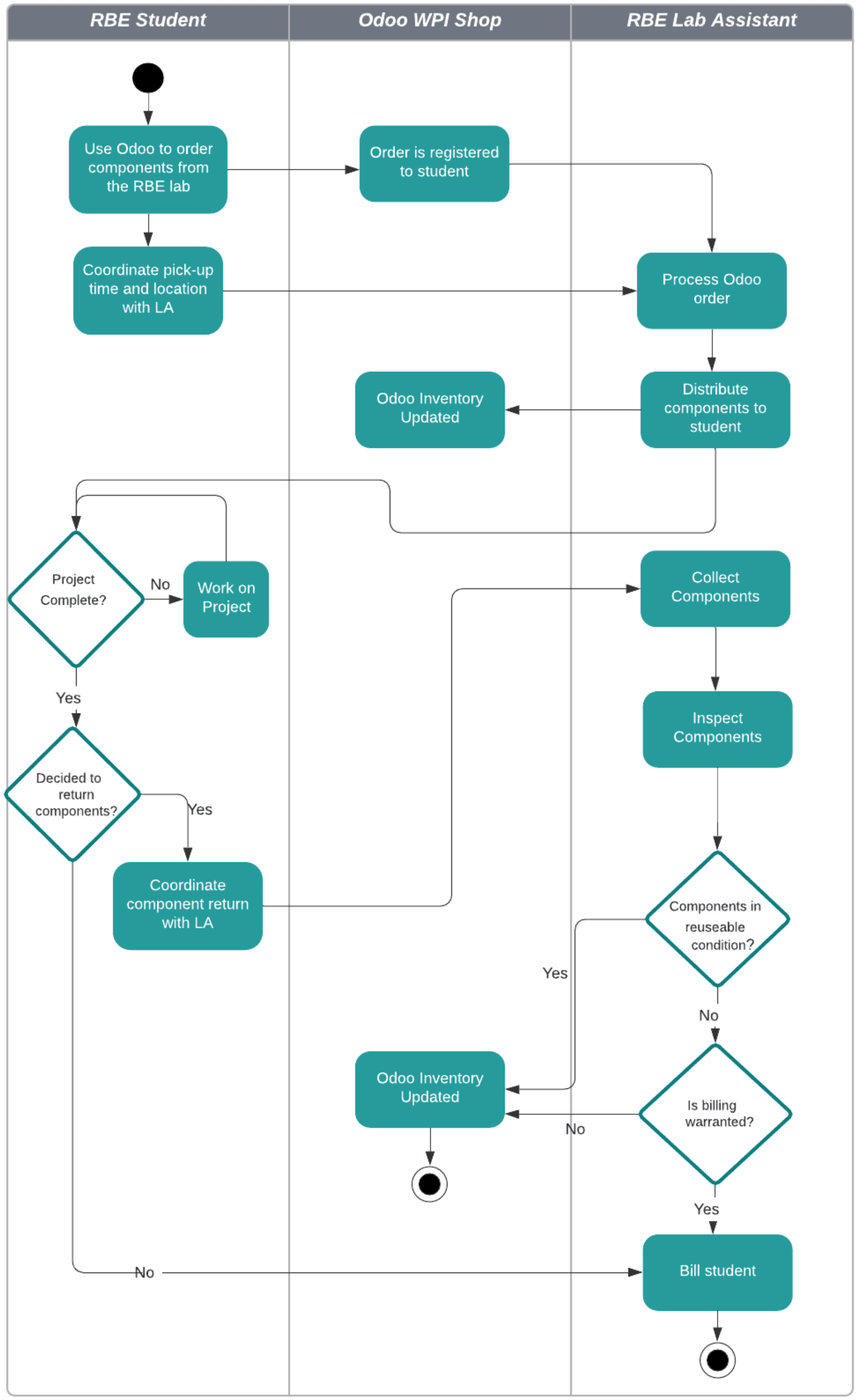


Figure 2.7: Current procurement process

2.2 Stakeholder Needs Elicitation and Analysis

Table 2.2 lists the needs for each of our four main stakeholders, as well as considerations that explain the reason for the need. This table is critical for knowing what the system should be able to accomplish. Without it, design choices could not be tied to any of the stakeholders, and therefore some features would be extraneous. Under each of the stakeholders, there is a tag (SH01, SH02, etc) that is used to connect them to Table 2.3. These tags are simply for Stakeholder 1, Stakeholder 2, etc.

Table 2.3 lists the important aspects of the project identified by the stakeholder and ranks each need from 1 to 3 where 1 is the highest priority and 3 is the lowest priority. The table lists the need, a statement describing the need, lists the associated stakeholders and the priority of the need. The priority was determined considering the number of stakeholders interested, and the resources available to the project (materials and time).

Table 2.2: Stakeholder Needs

Stakeholder	Needs	SH Considerations
RBE Lab Manager (SH01)	• Built with available parts • Open source • Sanitize components • Run at all times of day • Part tracking (inventory and to whom they are assigned) • Scalable • Limit person-to-person interaction • Distribute select components • Collect parts selected for return	Will be purchasing and managing the system. System needs to be made with parts available with the RBE Lab budget. Wants the potential for more component capacity. Wants to reduce human interaction for sanitary purposes.
RBE Lab Assistant (SH02)	• Limit interaction with ODOO • Ensure students get electrical consumables, hardware, microcontrollers, tools, motors, sensors • Ensure components are either returned or purchased • Ensure components that are returned are in working order	Two of the three LAs had Odoo related to aspects they least enjoyed. One of the main roles of these LAs is to make sure that the students get the components they need to succeed. At the end of the semester, the lab assistants are responsible for collecting the components from the student, and inspect the parts to see whether or not they have been damaged.
RBE Students (SH03)	• Fast and intuitive • Easy to access • Receive electrical consumables, hardware, microcontrollers, tools, motors, sensors • Return electrical consumables, hardware, microcontrollers, tools, motors, sensors	Students will be frequently using the system to get robotics components. The current system is slow due to lab assistance availability and hinders the student's ability to do well. The current process using ODOO is described as confusing. At the end of the semester, students that do not wish to keep their components must return them.
CERT (SH04)	• Sanitize objects sufficiently	CERT is responsible for the well being of all students on campus. If components are touched frequently, they should be cleaned with each use.

Table 2.3: Stakeholder Needs Analysis

Need	**Statement**	**Validation**	**Priority**
Limit person-to-person interaction	The system should limit person-to-person interaction to lower the spread of disease and sickness.	SH01	1
Scalable	The system should be scalable to allow for more inventory management.	SH01, SH04	2
High Accessibility	The system should be available during most of the day and in plain sight.	SH01	2
Fast and intuitive	The system should operate quickly and also be easy to understand for the users and management team.	SH01, SH02, SH03	2
Limit interaction with Odoo	The system should reduce/eliminate frustrations Lab Assistants have with Odoo.	SH01, SH03	3
Keep work open source	The project should be accessible to future contributors.	SH01	3
Sanitize components	The parts should be sanitized upon return.	SH01, SH04	3

2.3 Problem Statement

The goal of this project is to design an automated system that performs the component procurement process to decrease the wait time for students to receive components and reduce the transmission of diseases. To attain this goal, the system should be able to store needed components and distribute them to students, eliminate person-to-person contact be removing the need for a Lab Assistant to fulfill components requests, be scalable to allow for more inventory to be added in the future, and use readily available components in the Foisie RBE laboratory. The UML diagram in Figure 2.8 summarizes the system needs and shows how the process will differ from the current process shown in Figure 2.7.

2.4 Addressing Societal and Ethical Challenges

This system would be taking responsibility away from the LAs which has both positive and negative consequences. It was reported by all participants in our lab staff survey that collecting and distributing components was a major responsibility, along with helping students and other small tasks to assist the Lab Manager. Taking away the responsibility of distributing components may result in less work for the LAs and as a result, fewer may be needed. Three of the four Lab Assistants also enjoy helping students with component procurement but two of the Lab Assistants responded that fulfilling Odoo orders after giving out the components is the least enjoyable task of their job. Maintaining the system may also become one of their responsibilities, therefore restoring the need for the same number of LAs. Removing their involvement in the system may also solve some of their worst frustrations but the team will need to carefully consider what the shift in responsibility could do to their job security.

This system will also take up valuable space in the robotics lab, possibly replacing a space used for prototyping other projects. In the future, a team will need to consider potential locations to house the system that prevent exploitation of the system while also having the least negative impact on other student and staff resources.

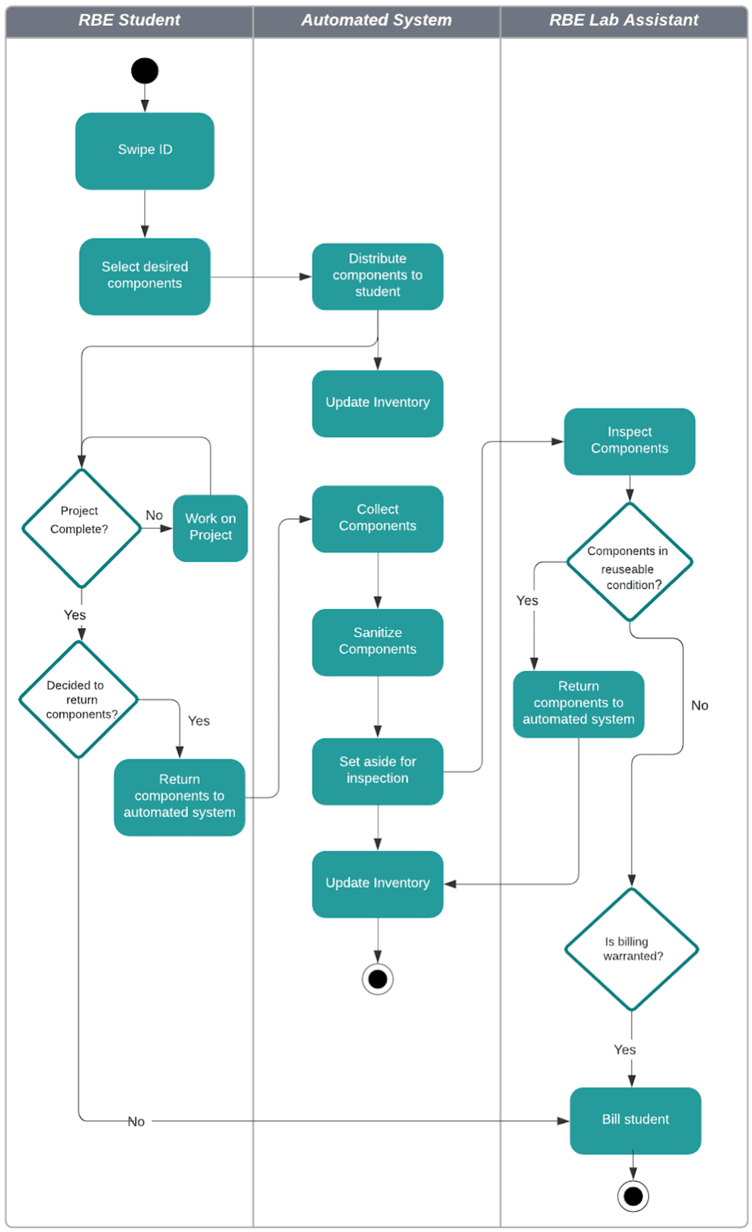


Figure 2.8: Proposed procurement process

Chapter 3

Materials & Methods

3.1 Design Concepts

The team began the design process by brainstorming and selecting high-level concepts to be implemented. These concepts are used to develop a set of technical measures so that the goals for the project could be set. Ideally, technical measures are created from the problem statement, but the only technical measure that could be taken from our data collection is that the user must be able to receive any component within 3 minutes of requesting it so that the system can keep up with a peak rate of 5 orders per hour with an average of 4 components per order. A single technical measure is not sufficient to begin designing so the team gathered more information from the Foisie RBE Lab Manager to determine more technical measures and requirements.

3.1.1 Components Storage

The first design concept explored was how the components in the automated system would be stored so that they can be retrieved for the user. The Foisie RBE Lab

Manager had requested that the component storage method be scalable so that more components can be easily added in the future and that the team use generic component storage bins as they are inexpensive and can be bought in bulk. The bin used is shown in Figure 3.1. To distribute components from these bins to the student, the system would bring the bin to the student, who would then take the number of components from the bin that he or she needs for the project. Alternatively, a robotic manipulator could be designed to remove components from the bin but this would be too difficult to implement given the project resources. The disadvantage of allowing students to take components out of the bins themselves is that the students may leave germs in the bin, which could be spread to students who later take components from the same bin.

Figure 3.1: Global Industrial Plastic Stack and Hang Components Storage Bin [4]

This bin is rated to hold up to 10lbs or about 4.5kg [4], allowing for the definition of the second technical measure, which is that the automated system must be able to lift 4.5kg of weight.

The bins are designed to be laid out on a wall rack as shown in Figure 3.2 [5]. This inspired the team to have the bins placed on shelves in a similar layout. For demonstration purposes, the team decided on a shelf with 3 columns and 2 rows each so the system has 6 components available. The bins are about 75mm tall and the team estimated that 25mm will be the additional height required to account for the thickness of the shelf and to make room for the bin to be lifted out from the shelf. Therefore each bin must be separated by 100mm vertically. With this design in mind, a third technical measure was created which was that the system must have a lifting range of motion of at least 200mm so that the system could access a shelf with 2 rows of bins.

Figure 3.2: Storage bin rack

3.1.2 Accessing the Components

The first option considered for accessing the component storage was a two-axis gantry system capable of moving a grabbing mechanism to an array of bins stored on a shelf. It is possible to design a gantry system that allows for fast, accurate, and precise motion in two dimensions. The disadvantage of this system is that the amount of bin storage would have a fixed size so if there was ever a need for more storage bins the gantry would need to be redesigned or multiple gantry systems would need to be built, adding considerable cost and complexity.

The second option was to use a mobile robot to drive to each bin location. The advantage of a mobile robot is that the robot itself does not need to be modified to change the size of the bin storage area and the bin storage area can be two or three-dimensional. A single mobile robot may be slower at retrieving component bins in the storage area than the gantry system but multiple mobile robots could be coordinated to retrieve multiple component bins at once to speed up the component procurement process for orders with many components. Another disadvantage to mobile robots is that localization, which is the ability for the robot to accurately determine its location within the work environment, can be difficult depending on the complexity of the environment.

The team chose to use mobile robots for this system because they offer greater scalability, which is a stakeholder need. Additionally, a mobile base designed by the Foisie RBE Lab Manager will be used since these mobile bases are readily available in the RBE Department and reduce the cost and design time required for this project. This robot, known as the Base Bot, can be seen in Figure 3.3.

With this mobile base selected, a localization system to ensure proper navigation around the storage area needs to be designed. This project proposes a solution that will organize the workspace into a grid, with pathways identified by straight lines marked on the floor and row and column indicators along the pathways. Storage bins and designated parking spots for the mobile robots will be set at specified locations within the grid. This allows the robot to both track its current position in the work environment and navigate to storage bin locations. These lines and indicators can be identified by a robot using a line follower sensor like the Pololu QTR8 reflective sensor. This sensor uses infrared (IR) light-emitting diodes (LEDs) to determine how reflective surfaces are. Black surfaces do not reflect light as well as non-black surfaces, and this can be detected by the sensor. By using black lines as markers, the robot can identify the markers using this sensor to both line follow and localize itself in the world. The robot firmware keeps track of the lines that the reflective sensor detects, and uses the orientation of the robot to determine whether or not to increment or decrement the row or column count. The robot is equipped with an Adafruit BNO055 inertial measurement unit (IMU) to measure orientation and rotations. There are also encoders on the drive motors, useful for measuring straight-line distances. Therefore, the team has opted to use the encoders for short straight-line distance measuring (like while approaching a bin or a parking space), the IMU for measuring rotation (for turning towards a bin or navigating the world), and the line-following sensor to navigate the pathways and detect the row and column indicators.

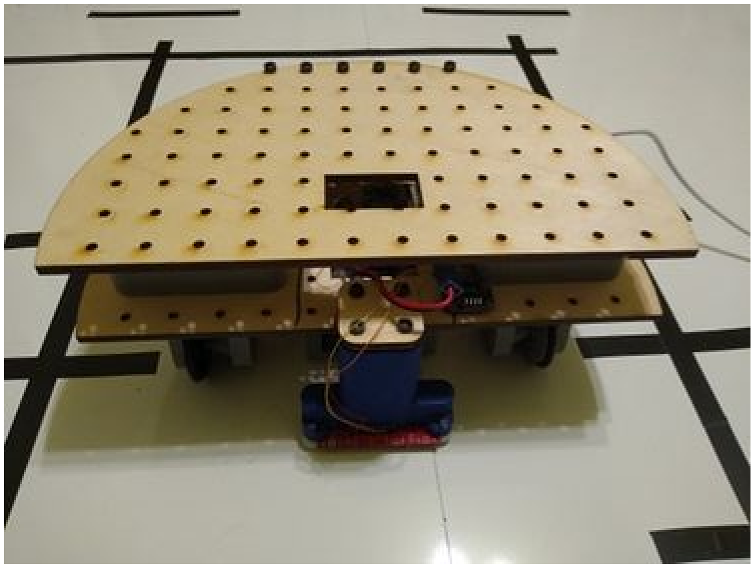


Figure 3.3: RBE200x Base Bot

The fourth technical measure was created with this mobile robot and its sensors in mind. This technical measure was that the robot must be able to track its position in the world so that it is accurate to the nearest row and column in the workspace grid.

To summarize, the technical measures for this project are:

- The user must receive their component within 3 minutes of requesting it to keep up with the peak rate of 5 orders per hour and an average of 4 components per order.

- The robot must be able to lift bins that weigh no more than 4.5 kg as per the load capacity of the selected bins.

- The robot must have a lifting range of motion of at least 200mm with movement accurate to within 1mm.

- The mobile robot must track its position in the world to the nearest row and column.

These technical measures are accompanied by some constraints and assumptions which are:

- The design must use components available to the Foisie Robotics lab
- The system is in a controlled and static environment

A set of system requirements were created from the technical measures, constraints, and assumptions. These system requirements are shown in Table 3.1. Each requirement has an associated test plan to verify that the requirement is met and help track project progress. Additionally, all requirements are traced back to a stakeholder need.

With these system requirements set, the team could proceed with designing the specifics of the system.

3.2 Mechanical Design

The mechanical design consists of the Base Bot, which was provided, the bin grabbing mechanism, and the lifting mechanism. A straddler was also added to the design for stability. Each of these components aside from the Base Bot is described in this section.

3.2.1 Bin Grabbing Mechanism

The robot needs to be able to grab storage bins and bring them to the user. In order to grab a bin, the team initially took inspiration from material-handling companies, which typically use forklifts to raise pallets with various loads. The team modified the forklift idea to be a spatula that slides underneath the storage bins. This design is mechanically simple but given that the chosen bins have less than 3 mm of ground

Table 3.1: Project Requirements

#	Requirement	Test Plan	Stakeholder
1	The system should be able to procure any component in the system no slower than 3 minutes to keep up with the peak rate of 5 orders per hour and average of 4 components per order.	The engineers will perform two tests, which change the robot's starting position. In the first version, the robot will start from its home location. In the second version, the robot will start from the kiosk location where it delivers bins. The engineers will start a timer and signal the robot to retrieve a component that is at the farthest position from the robot's starting location. In the second version, the robot must return the bin to the second farthest position before procuring the next bin for the user. Neither of the aforementioned tests should take longer than 90 seconds.	Students
2	The robot shall be able to lift 4.5kg.	The engineers will load a bin weighing 4.5kg and have the robot attempt to lift the bin. If it is successful then the test passes. If the robot breaks or is unable to lift the bin then the test fails	Lab Manager, Lab Assistant, Students
3	The lifting mechanism shall have a range of motion of at least 200mm and be accurate to 1mm.	The robot will be commanded to lift to various heights, which will be measured previously and marked. Once the lifting mechanism stops moving, the difference between the marker and the actual position of the lift is measured. Test passes if within 1 mm for each set-point, and a maximum height of 200mm is available.	Students
4	The robot shall report its position in the grid accurate to its row and column.	The engineers will use black electrical tape to design the layout of the system. This enables the robot to line-follow to specific locations, given their initial positions. Based on the robot's orientation, each perpendicular line in the world represents a new row or column. The test passes if it can correctly report its position in the grid.	Students

clearance, a 3D printed spatula would likely be too thin considering the weight of the loaded bins. The spatula could be machined from metal, but this was not available to use for the construction of this prototype and is not something the RBE laboratory can easily do. In order to use the spatula design, the bins themselves must be raised on standoffs to allow for the spatula to be thick enough to support 4.5kg and meet requirement 2. To raise the bin up, the team prototyped stand-offs that could be easily attached to the bins with an adhesive like hot glue. Although it is a simple modification, this would require that all the bins are modified in this way, hindering the ability to scale the system.

A second solution considered was to use a parallel gripper mechanism to grab the bins from the side, removing the need to modify the bins. A parallel gripper would require more clearance between each bin than other design options reducing the number of bins that can be stored in the same space. Additionally, a parallel gripper requires an actuator, adding complexity to the design. The final design option utilizes a lip on the back of each bin, which is normally used to hook the bin onto a storage rack, as shown in Figure 3.2.

The team designed a cleat that hooks into this lip so that the bin can be lifted and moved. This design is mechanically simple, like the spatula, but does not require any modification to the bin. Additionally, this design does not require side clearance to grab the bin or need an actuator as the gripper does. This solution was chosen for grabbing the bin because of its simplicity and lack of modification to the bin. The final design of the cleat includes a limit switch that is used to detect when contact is made with a bin. The cleat is shown in Figure 3.4.

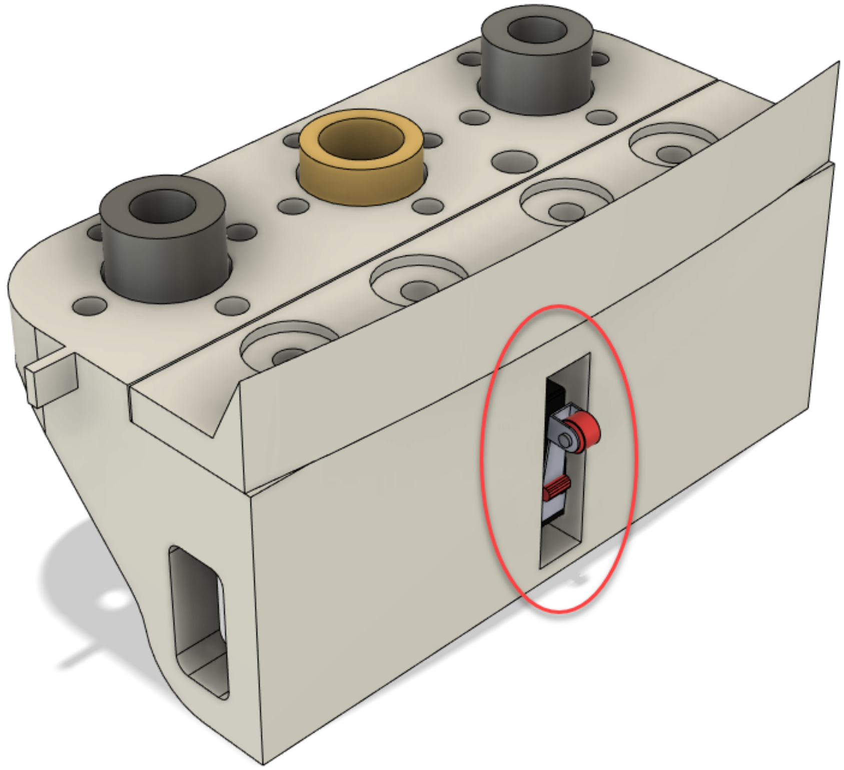


Figure 3.4: Limit switch circled on cleat assembly

3.2.2 Lifting Mechanism

To accompany the cleat, a lifting mechanism was designed so that the cleat can reach different shelf heights and lift the bin off of the shelf. Three designs were explored for this task. For the linear motion, all designs use two smooth steel rods and bearings on which the cleat will move along. Smooth steel rods and bearings are inexpensive compared to other options like linear rails and offer smooth linear motion. One of our stakeholders, the Foisie RBE Lab Manager, had many high-power Pololu 37D 50:1 gear motors available so the first two designs had this motor in mind.

The first design uses a chain and sprocket to drive the cleat along the smooth steel rods. In Figure 3.5, the sketch used for the calculations is shown. M is the mass in kg of the cleat and bin assembly, r is the radius of the sprocket and T is the torque provided by the motor. With a mass of 4.5kg (about 10lbs) which is the maximum weight supported by the bin and the motor torque of 22kg·mm from the motor at optimal efficiency, the needed sprocket radius is 4.9mm.

$$r = \frac{T}{M} = \frac{22kg \cdot mm}{4.5kg} = 4.9mm \tag{3.1}$$

A sprocket of this radius is not standard and would require a specially made chain, making this option not possible with our budget and time constraints. Additionally, the motor would need to be stalled to keep the cleat at a specified height, which would be power inefficient and reduce the life of the motor.

The next design utilizes a lead screw to make the design not back-drivable. This means that if the motor is turned off, any external forces acting on the cleat, such as the weight of the bin, will not cause the cleat to move. This solves the motor stall problem of the previous design since the motor can be powered off after raising the cleat to the desired height. By designing a platform to attach to a screw-nut, and constraining it to move linearly along the two steel rods, the vertical motion of the lift is achieved by simply rotating the leadscrew.

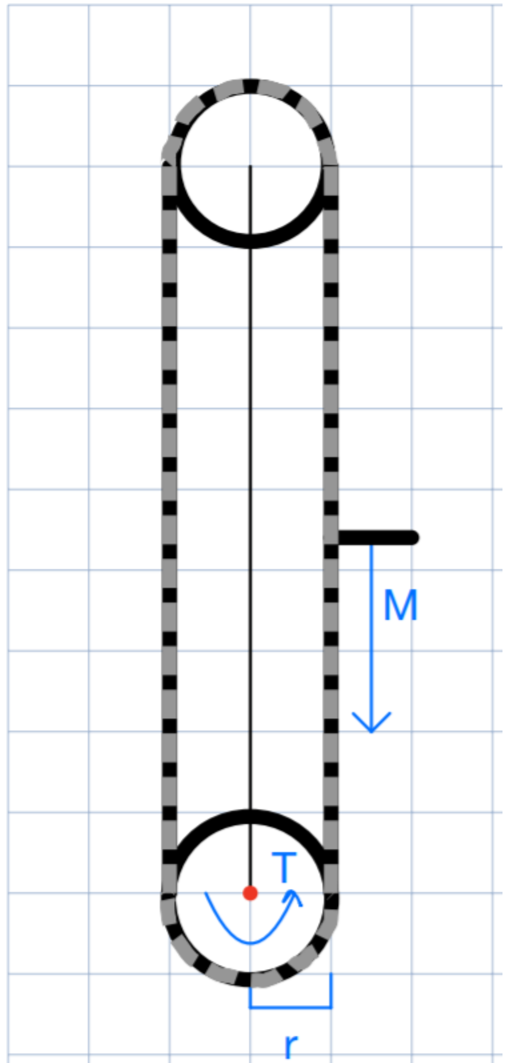


Figure 3.5: Chain and Sprocket free-body-diagram

There are two main considerations to consider with this design. The leadscrew and the actuator. The lead distance is the length of linear travel per rotation of the leadscrew and is dependent on both the distance between the threads (pitch), and the number of threads on the rod [6]:

$$Lead = NumberOfThreads * Pitch \tag{3.2}$$

This is important to keep in mind as it is one of the factors that determines the height precision. For example, spinning the leadscrew 1 degree with a lead of 2mm would raise the payload by 0.0055mm. The lead distances of the lead screws the team found while sourcing parts are between 2mm and 8mm, which allow for very precise movement. However, when the lead distance is increased the leadscrew may not be self-locking, causing it to backdrive. To determine if the leadscrew is self-locking. the following condition must be met [6]:

$$\pi \mu d_m > L \tag{3.3}$$

Where μ is the coefficient of friction between the nut and the lead screw, d_m is the mean diameter of the lead screw in meters and L is the lead distance in meters.

To meet this condition, a lead screw with a coefficient of friction of 0.15 [7], must approximately have a lead distance of less than 4.712mm if the screw is 10mm in diameter. To stay well under that estimation the team chose to go with a lead distance of 2mm.

Another attribute to consider on the lead screw is the thread shape. The most common shape is ACME threads, which are trapezoidal and allow for greater strength at the cost of slightly more friction than square threads [8]. An image illustrating the shape of these threads can be seen in Figure 3.6. Since the system should be able to support heavy weights, the team decided to use a screw with ACME threads.

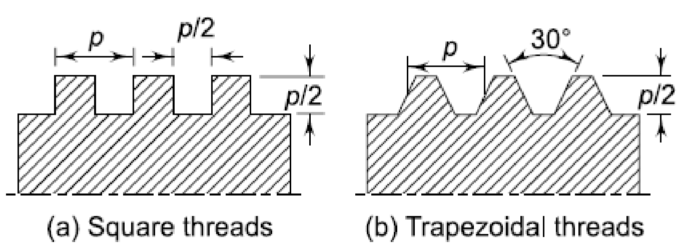


Figure 3.6: Two lead screw thread types [8]

To select a motor for this design, the torque needed to lift and lower the workload was calculated using the following equations [6]:

Torque to raise workload:

$$\tau_{Raise} = \frac{Fd_m}{2}\frac{\pi\mu d_m + L\beta}{\pi d_m\beta - \mu L} \tag{3.4}$$

Torque to lower workload:

$$\tau_{Lower} = \frac{Fd_m}{2}\frac{\pi\mu d_m - L\beta}{\pi d_m\beta + \mu L} \tag{3.5}$$

Where: d_m is the mean diameter of the lead screw in meters, β is the thread geometry parameter, which is calculated using the angle of the thread shape. This parameter is 0.968 for standard ACME threads with a thread angle of 14.5 degrees and 1 for square threads which has a thread angle of practically 0 degrees. F is the force exerted on the screw in Newtons from the workload mass, μ is the coefficient of friction between the nut and the lead screw and L is the lead distance in meters.

With a 10mm diameter lead screw that has a lead distance of 2mm, a brass nut and machine-oiled steel screw which gives a friction coefficient of 0.15 [7], and standard ACME threads, the torques required to raise and lower a workload were calculated. These calculations are in Table 3.2 and were done with three masses. The first is just the weight of the cleat, the second is the cleat plus the required lifting capacity, and the third is the cleat plus double the lifting capacity to ensure a safety factor of two.

The motor the team had readily available had stall torque of 2.06Nm, but with a max RPM of 200 at no load [9]. At 200RPM, with a 1:1 transmission, the workload on the leadscrew would travel 6.6mm/s, which would mean that the robot would take about 16 seconds to clear one shelf height (with the shelf height at about

Table 3.2: Lifting Torque Requirements

Mass (kg)	Raising Torque (Nm)	Lowering Torque (Nm)
0.5	0.0052	-0.0022
5	0.0523	-0.0215
9.5	0.0994	-0.0407

100mm). The speed could be improved by using a gear ratio to multiply the speed by 2 or 3 but at the cost of space. Of the motors with the same form factor, the fastest motor has only 0.049Nm of stall torque which is not enough even for the bins at max capacity on the cleat-assembly(5 kg total). The second fastest motor, which operates at 1600RPM no-load [9], does have enough stall torque (0.29Nm) [9], so the team calculated the raising speed for a 1:1 transmission at different torques for both the prospective motors in Table 3.3. From here the 200RPM motor will be referred to as Motor 1, and the 1600RPM motor will be referred to as Motor 2.

Table 3.3: Motor Comparison

Mass (kg)	Torque Needed (Nm)	Height per Second at Required Torque (mm/s)	
		Motor 1	Motor 2
0.5	0.0052	6.6489	50.7594
5	0.0523	6.4887	42.5949
9.5	0.0994	6.3286	34.4302

From Table 3.3, it can be seen that Motor 2 produces measurements that would make clearing each shelf at least 6 times faster than using Motor 1. Each motor also has an encoder resolution that allows for a height precision of less than 1mm.

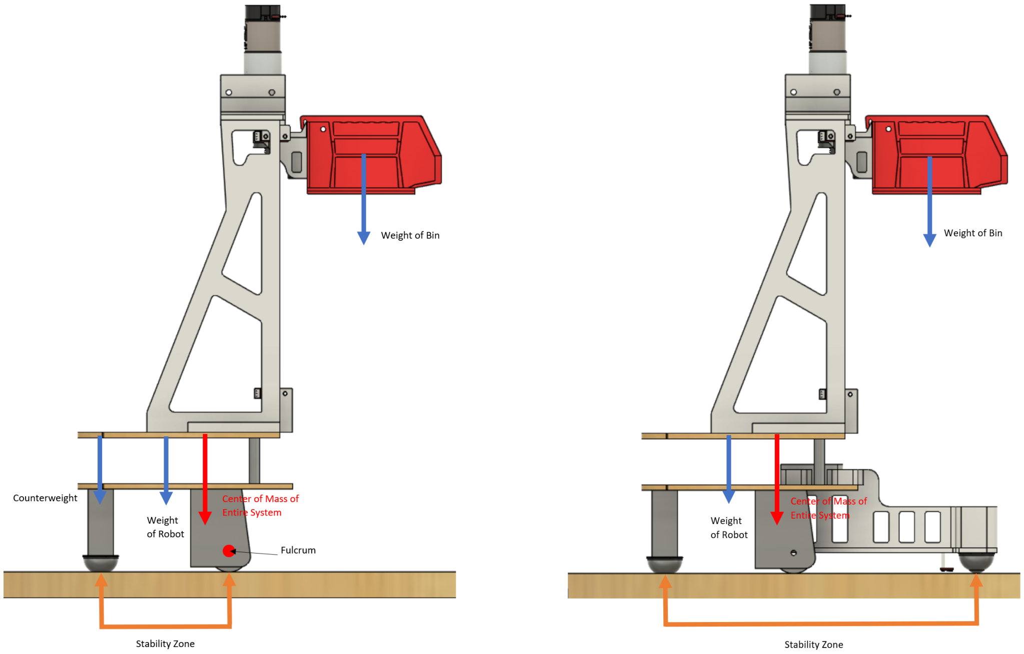
So with this decision, the team decided to use Motor 2 in a 1:1 transmission, that will drive a 10mm lead screw with a lead of 2mm.

3.2.3 Stability

Since the lifting mechanism is being rated to lift 4.5kg, a stability analysis was performed. The robot has two driving wheels along the same axle with a caster wheel in the back. If the center of gravity of the robot with the loaded bin is not between the points of contact with the ground of the driving wheels and the caster wheel then the robot will tip over. This area is shown in Diagram A of Figure 3.7 and is labeled as the "Stability Zone".

The weight of the bin is clearly shown outside of the "Stability Zone" so if the weight is large enough the robot can tip over. To prevent this, two options were explored. The first was to add a counterweight to the back of the robot to counteract the weight of the bin and shift the center of gravity back in between the three points of contact. The second approach is to add another caster wheel in front of the robot to increase the area that the center of gravity of the robot can be at without the robot tipping. This mechanism will be referred to as a straddler in the remainder of the paper. To evaluate the first option, the mechanical design is assumed to be as specified above, with estimated distances to the heaviest components such as the lead screw, the smooth rods, the battery, and the bins at their safety factor with the cleat (9.5kg), from the wheels to calculate the sum of the moments. With these system weights considered, approximately 6kg of weight would need to be placed on top of the back caster wheel to ensure stability.

The second option which uses a straddler is a simple approach that some industrial forklifts use and is shown in Diagram B of Figure 3.7. The straddler would extend only as far as the bin would extend when it is being held by the robot so that the addition of the straddler does not affect the maneuverability of the robot within the work-space. Since the weight of the bin will always be behind the straddler's caster, this option would allow the robot to lift a bin of any weight that does not



(a) Stability without Straddler

(b) Stability with Straddler

Figure 3.7: Stability Comparison

cause structural failure (such as the straddler arm or robot frame breaking) and not tip over.

The straddler also could be used to attach the line sensor further in front of the robot. Moving the line follower sensor further from the robot's center of rotation allows for smoother line following by making the sensor less responsive to small changes in the robot's orientation. This approach was chosen since the team can prototype the straddler with materials on-hand.

3.3 Software

In this section, the firmware that controls the mobile robot, the Graphical User Interface (GUI), and the communication protocol between them are discussed in detail. The base of the robot firmware is a state machine that contains all of the instructions to navigate the workspace and handle the component bin delivery to and from the user borrowing components. Fig. 3.8 shows a high-level overview of the firmware responsible for procurement.

When a command to retrieve a bin is received, the robot starts by navigating to the specified bin. Once navigated to the correct row and column, the firmware uses the encoder on the motor that controls the lift mechanism to raise the lifting cleat to the height of the level of the desired bin. It is important to note that given a shelf height, the firmware commands the lift to move just below the lip of the bin so that the cleat can hook into the bin properly. Once at the correct row, column, and lift height, the robot drives forward and follows the line up to the bin. As shown in Figure 3.4, the cleat assembly incorporates a limit switch, which is used to determine when a bin has made contact with the cleat. Once contact has been made, the lift raises so that the cleat hooks in and lifts the bin off the shelf. The robot now moves away from the shelf, again in a straight line, until it reaches the grid representing the world. At this point, the robot has grabbed the bin and is ready to deliver it to the student.

The process of returning a bin is almost identical, just in reverse order. Once a component has been procured for the student and the exchange has been confirmed, the robot receives a command to return to the row and column where it obtained the bin initially. Once it reaches the desired location, it will raise the lift to a certain height. Since the bin is in the robot's possession, the lift is raised past the shelf height so that it can be placed on the shelf. The robot approaches the shelf until it reaches a line marker, indicating that the bin is entirely over the shelf. At this point, the robot lowers the lift and lets the bin rest on the shelf. The robot navigates back to the grid and waits for its next command.

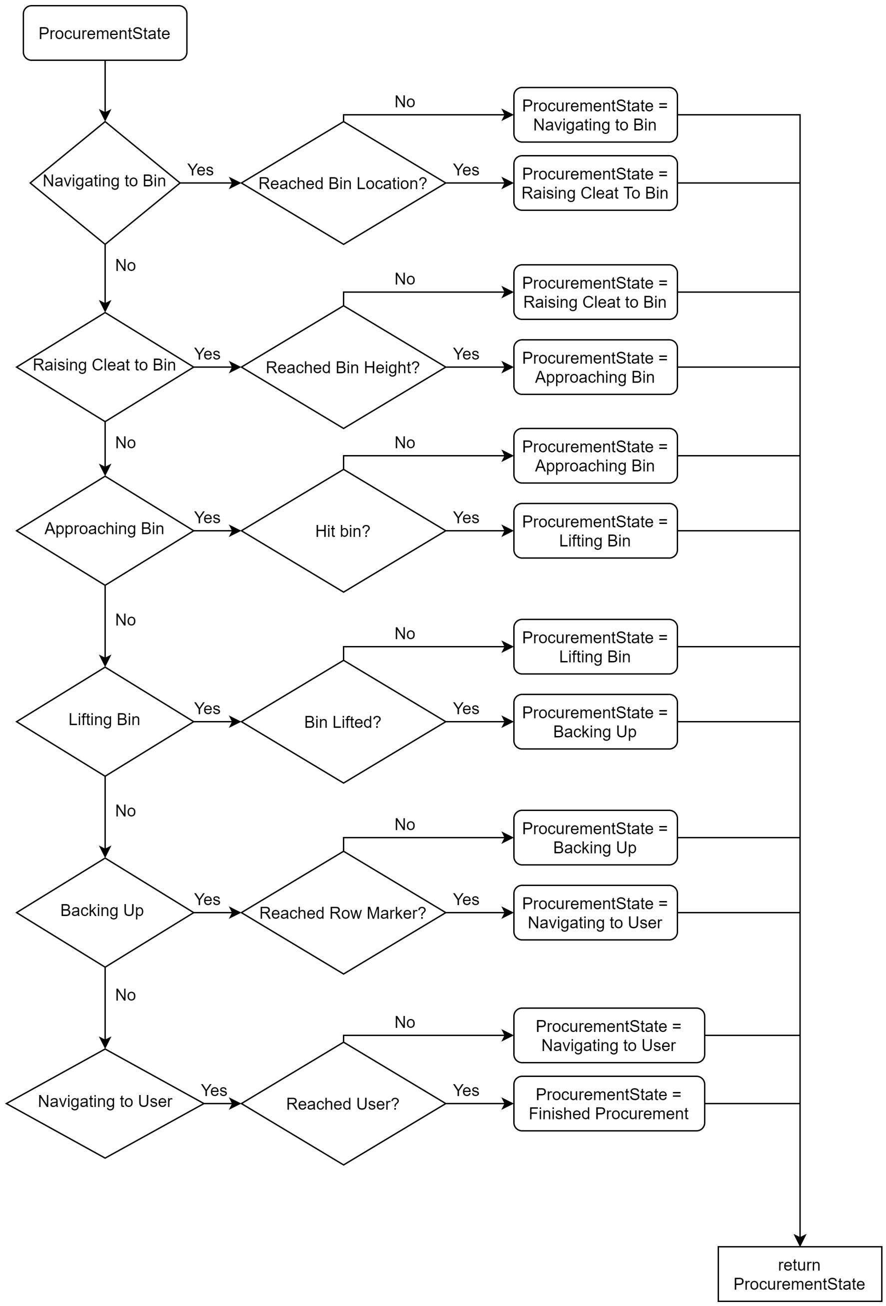


Figure 3.8: High level flow of the Procurement Firmware

Commands for retrieving and returning bins to the storage area are sent from the system's Graphical User Interface (GUI). A GUI was chosen as the method for the user to interact with the robot because it can provide a simple, user-friendly experience.

Java was chosen for the GUI creation because previous work had already been completed that demonstrated how to have a GUI communicate with the mobile robot base chosen for this project. Building off of that example would decrease development time, allowing for more time resources to be used in other areas of the project. To store the inventory of the system, a Javascript Object Notation (JSON) file was used. The JSON file format can be edited easily by humans with a text editor, which allows for the inventory to be modified without the need for an additional GUI for this purpose. A GUI for updating inventory would be beneficial but is out of scope for this project. The JSON file format is also easily parsed programmatically with existing libraries for Java. Another JSON file will be used to save the inventory that has been borrowed by the students.

The proposed GUI first prompts the user with a welcome screen where students can enter their student ID number, and proceed to the next screen to request components. The component request screen presents the component names and their available stock in a list that the user can click. Clicking on a component in the list brings the user to a "check out" screen where they specify the number of the component they intend to take. Additionally, there is a text entry where the student identifies which RBE course they require the components for. In this same window, the GUI will specify whether or not the component needs to be returned at the end of the semester. The robot will begin retrieving the requested component and prompt the user for further action as necessary. Figure 3.9 describes the full flow diagram of the GUI.

The GUI and the robot firmware communicate using the User Datagram Protocol (UDP) over a WiFi connection. With this protocol, the GUI sends a packet of information over the network with an ID and sixteen 32-bit floats (only the first 3 of the 16 floats are ever used in this implementation). The robot firmware receives the packet and reads the ID number. This ID number corresponds to a command and then the associated data is used to execute the command. For example, the row and column to which to navigate are each represented by the first two floats in the UDP packet of a navigation command. In the retrieve and return bin commands, the shelf height is also sent as a third float in the UDP packet. The robot firmware continuously sends packets containing its own status information back to the GUI. The GUI listens to these status messages and uses them to determine when the robot has completed retrieving or returning a bin from the shelf.

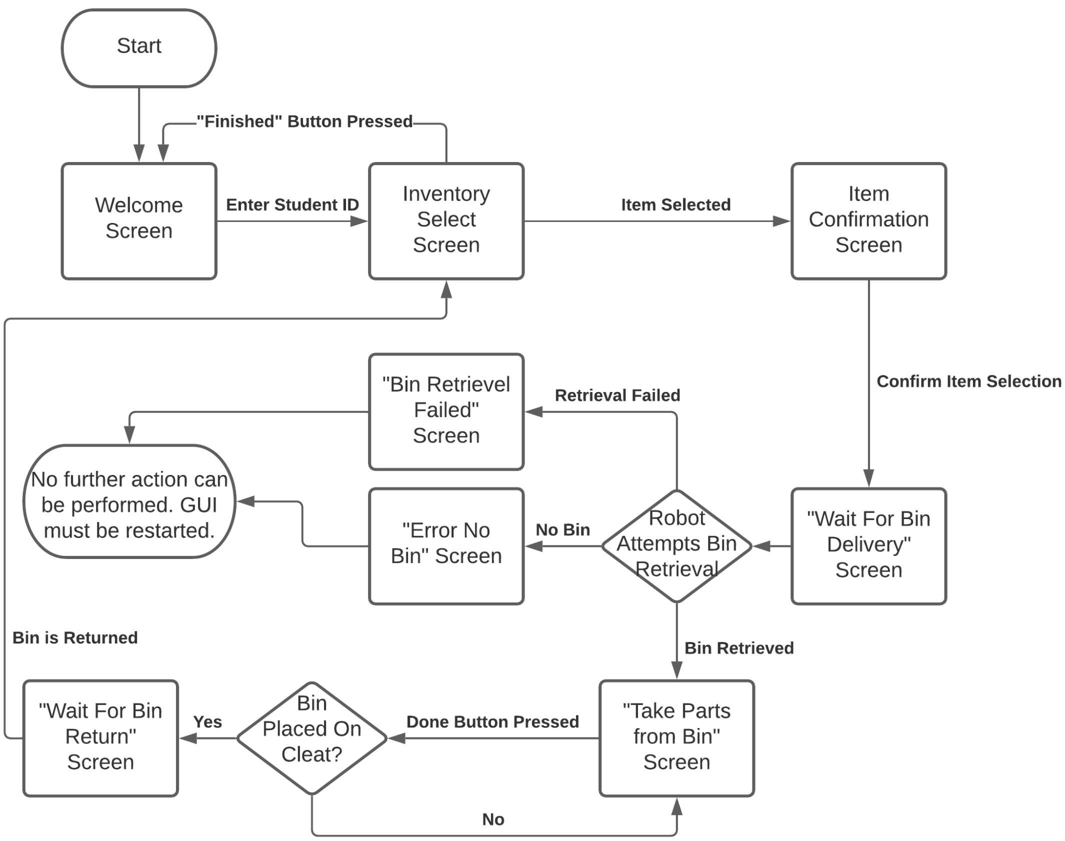


Figure 3.9: Flow of GUI

3.4 Architecture and Flow

Figure 3.10 presents the architecture of the warehouse robot system. The portion of the diagram that is labeled "Odoo" was not implemented and is intended to be completed by future teams.

The "GUI" section includes all of the functionality for which the GUI is responsible. As discussed in the "Graphical User Interface" section, the student will be primarily using the GUI for requesting components, and thus the GUI is responsible for keeping track of the inventory of each component, as well as commanding the robot to perform the component procurement and return. The commands are published via UDP and sent to the firmware, which processes them. The GUI also keeps track of what the robot is currently doing, so that the GUI can instruct the student of the next steps once a robot reaches a certain state. The robot updates the GUI with its status information via UDP. Eventually, the GUI will interface with Odoo (represented by the "Odoo" section), which will be responsible for billing the student for damaged or purchased components, as well as keeping track of inventory on a server, instead of locally on the machine that is running the GUI.

Finally, the section labeled "Robot" lists all of the robot's functionality and responsibilities. The robot firmware is responsible for interpreting commands sent from the GUI and updating the GUI with the robot's status. It is also responsible for executing subroutines such as Navigating, Parking, Bin Delivery, and Bin Return. All of these routines use sensors such as the Polulu Qtr8 reflective sensor, Adafruit BNO055 IMU, encoders, and limit switches. Figure 3.11 shows a flow diagram of the component procurement process using the warehouse robot system that focuses on the interaction between the GUI and the robot firmware.

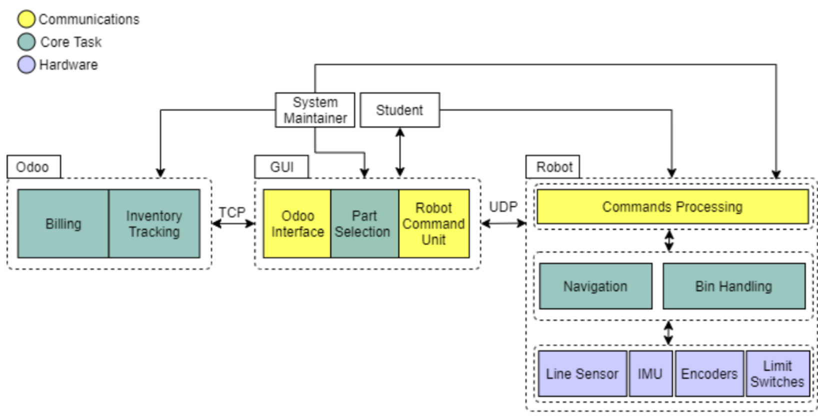


Figure 3.10: System architecture diagram

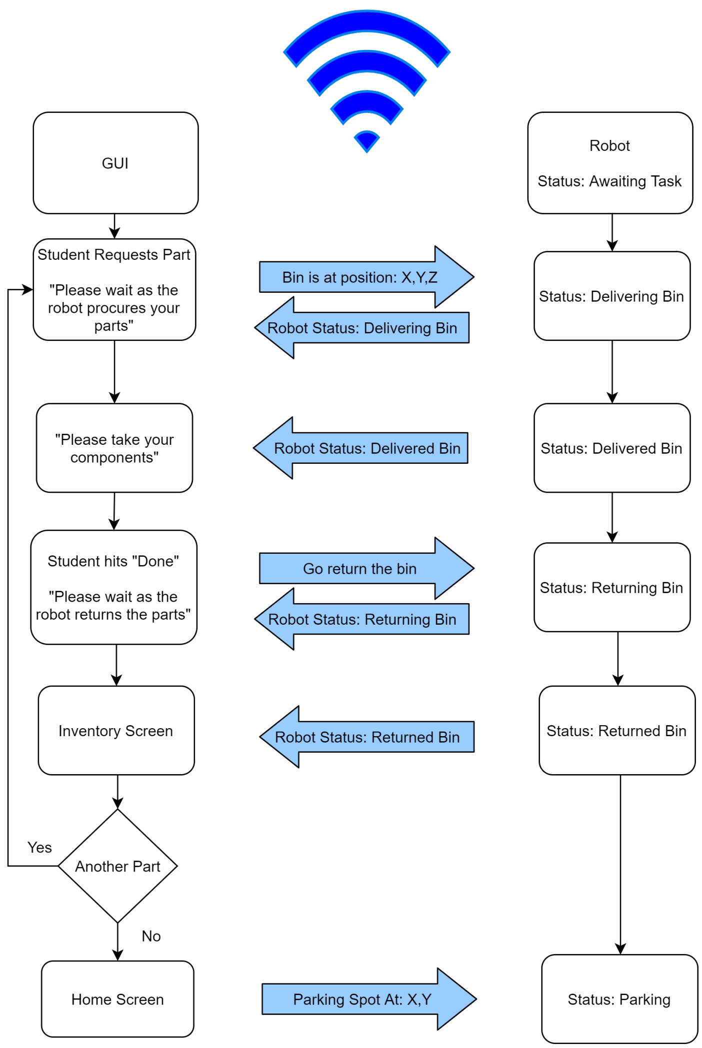


Figure 3.11: System flow diagram

Chapter 4

Results

4.1 Prototyping

During the prototyping process, several revisions of the lifting mechanism and navigation systems were made so that the system could meet the requirements of the project. The lifting mechanism had the most severe problems since it could only lift about 25% of the weight that the mechanism was designed for initially and would vibrate violently. The navigation redesigns were to improve the reliability of the procurement process.

4.2 Lift Mechanism: Version 1

The first lifting mechanism featured a lead screw that was driven by a 1600RPM Pololu 37D motor. The transmission of torque from the motor to the lead screw was done through spur gears. Spur gears were chosen as opposed to directly attaching the motor to the lead screw so that the gear ratio could be changed if necessary. This design is shown in Figure 4.1.

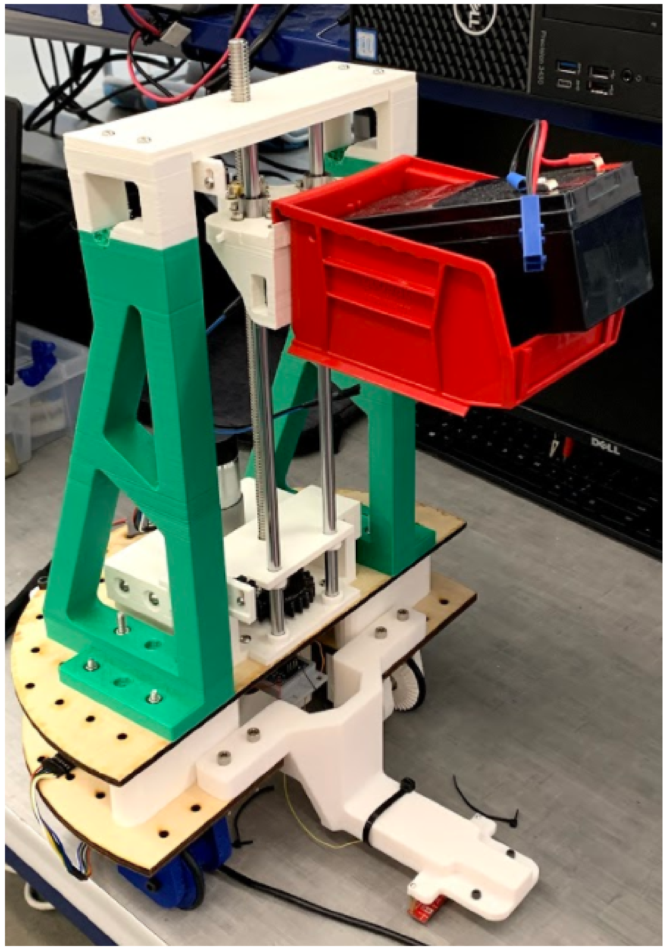


Figure 4.1: Lift mechanism version 1

However, this had unforeseen consequences that resulted in large amounts of friction present in the lift mechanism that severely reduced the amount of weight capable of being lifted. During initial testing, the lift mechanism could lift no more than 2.25kg and struggled to do so. The friction was due to inefficiencies in the gears from 3D printing and from the gears rubbing against the bottom of the gearbox. Screws linked the 3D printed gear to a coupler that attached the gear to the lead screw but the friction these screws would create was underestimated, especially with 4.5kg pressed down on them.

The team performed a static load test to observe the structural integrity of the robot. The lift mechanism was able to hold 9kg on the cleat but the straddler deformed under the 9kg load so a redesign was needed to prevent tipping. To rectify this, the team redesigned the straddler to be substantially thicker with many more mounting points to give it strength.

4.3 Lift Mechanism: Version 2

The second iteration of the lifting mechanism, seen in Figure 4.2, featured a reinforced straddler for rigidity and the motor was relocated to the top of the lift truss so that it could directly drive the leadscrew. The lead screw was also moved to be in-line with the two smooth steel rods. This greatly reduces the lever arm created by the bin weight and also allows for the smooth steel rods to provide more of the counter-torque required to hold the cleat in place. This eliminated the torque loss from the gears, as well as the friction caused by the gears and screws rubbing against the bottom of the gearbox. Additionally, the entire system became substantially quieter and had smoother lifting motion. These changes allowed the lift mechanism to efficiently lift 4.5kg, meeting the lift weight requirement of the project. The straddler was able to support this weight without visible deformation but both structural plates of the Base Bot bulged upward in response to the stress of the 4.5kg load. The team attributes this deformation to the structural rigidity, or lack thereof, of the plywood plates that make up the top and bottom portions of the robot. With prototyping materials such as plastic and thin plywood, the team acknowledges that some flexion in the design is difficult to remove entirely, but the team asserts that if system components were machined from aluminum the bulging may not occur within our bin weight operating range. The full bill of materials for our final design can be found in Appendix C.

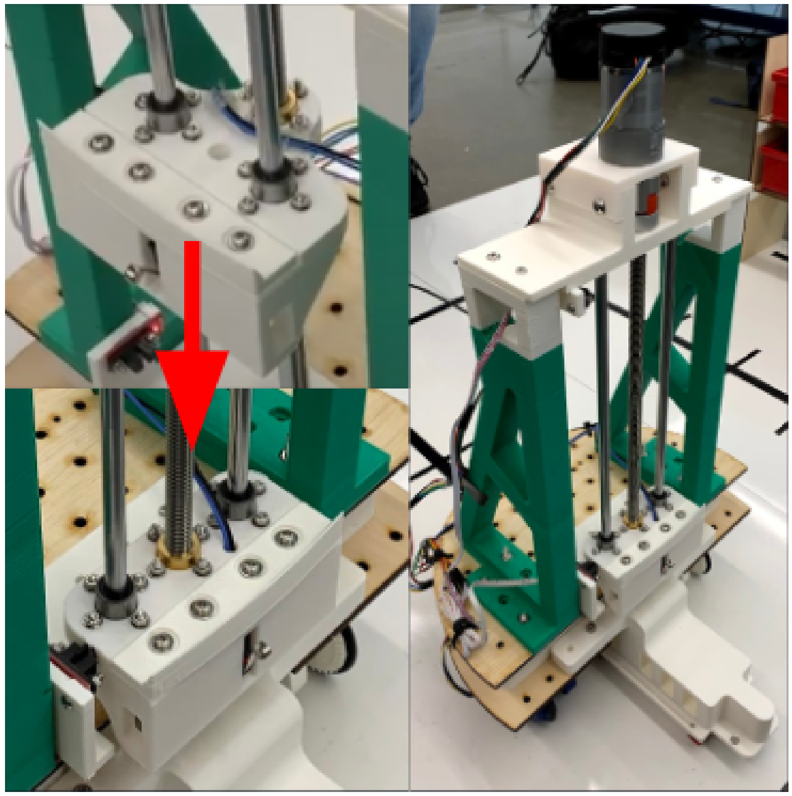


Figure 4.2: Leadscrew position change (left). Version 2 (right)

4.4 Navigation: Version 1

The firmware was initially written for a separate Base Bot that was nearly identical to the one used for the prototype. Originally, the idea was to have two rows and three columns each with its own indicator type. Row indicators were made of three separate lines that constructed a square shape with a missing side. Figure 4.3 shows the row indicators as well as other elements on the floorplan. This is indicator shape is due to the distance between the line sensor and the center of rotation (COR) of the robot. When the line sensor reaches any of these lines in the row indicator it knows when to turn so that it stays lined up on the path. This solution, although valid, was not intuitive to set-up, and therefore it was not easily scalable.

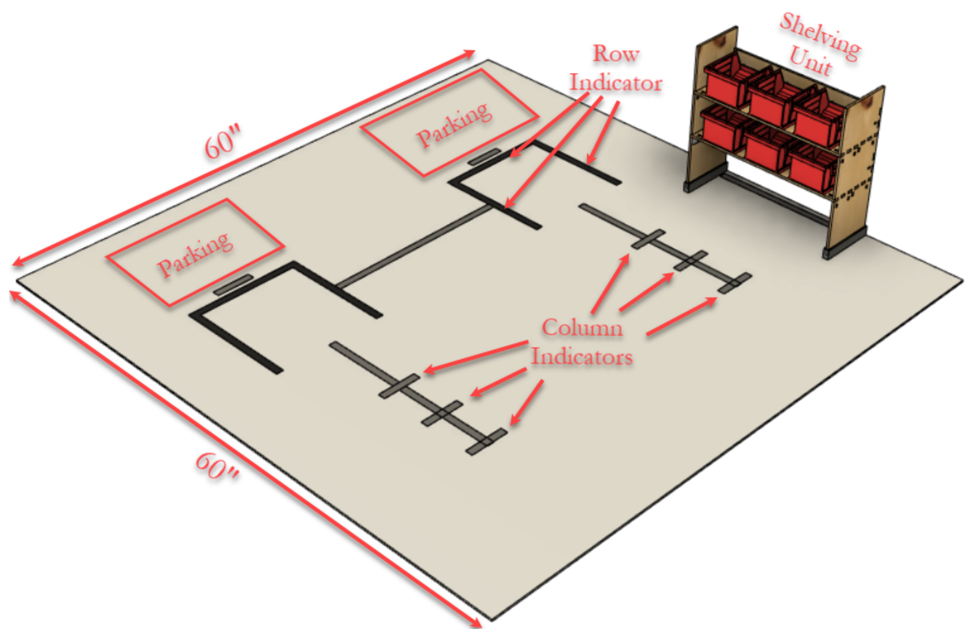


Figure 4.3: First proof-of-concept floor-plan version

4.5 Navigation: Version 2

To address the issue of scalability and intuitive setup, the floor plan was remade, such that the column markers and row markers were both singular lines. This change to the row markers is shown in Figure 4.4. Instead of the double-lined approach discussed in Navigation: Version 1, the single lines meant that the row indicator could be placed exactly where the row will be, instead of two lines that surround the row symmetrically around the robot's COR. The navigation firmware handles this by using an additional line sensor, mounted directly below the robot's COR. This way, one line sensor can be used at the front of the robot, used only for tracking the line, while another one, directly below the robot's COR is used for determining the robot's position in the world by counting the row and column markers.

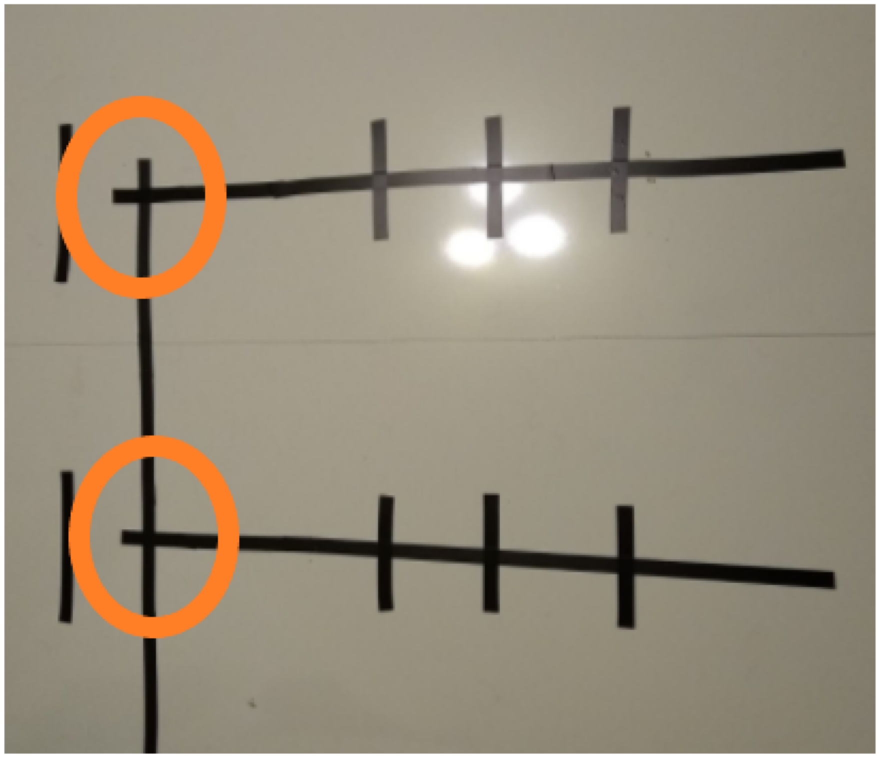


Figure 4.4: Floor-plan version 2 with new row indicators

4.6 Experiments

The final system design was tested to verify that the system requirements were met. These tests were also used to assess the efficiency and reliability of the system and to identify areas for future improvement.

4.6.1 Lifting Force

To test that the robot can lift the required 4.5kg (10lbs) a bin was filled and measured to weigh 4.55kg and loaded on the lifting cleat. The lift position began at 0mm and then the lift was set to raise the bin 200mm, which is nearly the entire length of the lift movement. The lift mechanism was able to lift this weight successfully, verifying the lift weight requirement. This experiment was performed three times. Although the robot was able to lift this weight, the Base Bot bowed under the weight, and no more tests with this weight were performed to mitigate the risk of structural failures. Future work should consider using stronger materials.

4.6.2 Lift Position Accuracy

The range of motion of the lift is 244mm which meets the design requirement of at least 200mm of motion. To verify the second portion of requirement 3, the accuracy of movement of the lift was tested with the following testing procedure:

1. Place the payload (0kg, 1kg, 2kg) in a bin and place the bin on the cleat of the robot.

2. From position 0, command the robot to lift the workload to the position for the second shelf (131.68 mm) from the maintenance GUI.

3. Measure the height of the lift and record the error.

4. Repeat the steps 1-3 for 10 trials.

5. Repeat step 4 for 0kg, 1kg, and 2kg workloads.

Figure 4.5 shows box plots of the results from this test. The lift met requirement 3 when lifting 0 and 1kg but on one occasion the lift did not raise high enough for 2kg, although this was only by 0.3mm. This problem is due to improperly tuned PID gains for the lift, rather than a physical limitation of the lift itself. When the lift raises the weight, it often overshoots and oscillates before settling down but does not settle to the same height every time, resulting in the variance shown in each box plot. A full table of the results for this test can be found in Appendix D.

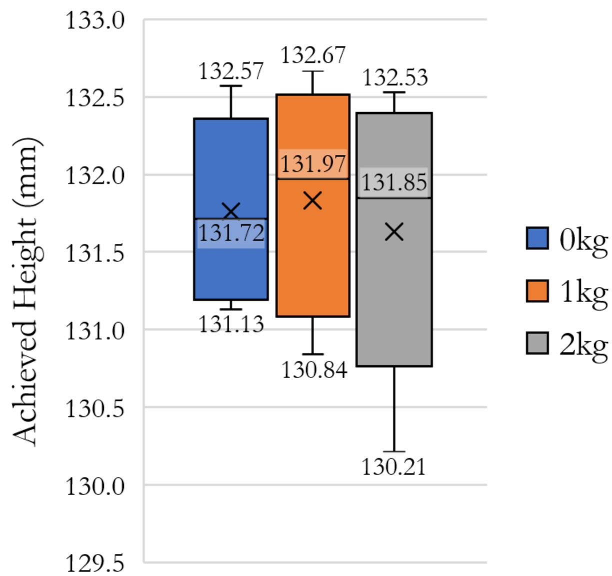


Figure 4.5: Lifting Results Box Plot

4.6.3 Navigation Accuracy

For the navigation testing, locations in the grid are denoted as [x, y] where x represents the row of the grid and y represents the column of the grid. To test the navigation, the team used the following testing procedure:

1. Place the robot on a starting location on one side of the map [1,-3]
2. Place the workload (0kg, 1kg, 2kg) in a bin and place the bin on the cleat of the robot.
3. Command the robot to go to a position on the other side of the map [2,-3]. After the robot completes navigation, visually inspect that it has reached the correct location.
4. Send the robot to its starting position.
5. Repeat steps 1-4 10 times.

6. Repeat step 4 for 0kg, 1kg, and 2kg workloads.

Of the thirty trials conducted, the robot was able to navigate from one side of the map to the other successfully in all trials, regardless of weight. A full table of the results for this test can be found in Appendix E.

4.6.4 Procurement and Return Accuracy

To test the reliability of the procurement and return, the team used the following testing procedure:

1. Place only three bins of various weights on the shelf: Empty, 1kg, 2kg. Make sure at least one bin is at each shelf height.

2. Start the robot from a parked position and using the GUI, request a bin with the current testing weight (start with 0kg).

3. Time the procurement starting from the moment the user hits start and end it when it reaches the user. If the run failed, indicate a failure for the trial.

4. Time the return starting from the moment the user hits return and end it when the components are returned to the shelf where they were retrieved. If the run failed, indicate a failure for the trial.

5. Repeat steps 2-4 for 10 trials with each weight specified in step 1.

The robot was able to procure and return bins of various weights 25 out of 30 attempts. In the 2kg test, the robot was able to successfully procure and return a bin in nine of the ten trials, but in one of the trials the lift did not raise the bin high enough. In this trial, the bottom of the bin caught the shelf and began to tip it over.

During one of the 0kg trials, the robot dropped the bin after having successfully grabbed it off the shelf. However, the bin landed on the straddler and was successfully delivered to the user but could not return the bin to the shelf. The team attributes this to a slight misalignment when approaching the shelf. The future work chapter addresses strategies to minimize misalignment risks. Furthermore, in this same trial, the robot needed a slight nudge while turning as it did not reach the desired heading, before starting to return. Once the robot was nudged, the return was successful. This could be a function of the battery voltage, but more likely the robot's PID gains may need further tuning, especially depending on the payload the robot will be carrying. The team also noticed that sometimes the wheels of the robot would slip on the white-board used as the field for this prototype.

During three of the 1kg test trials, the robot improperly detected an empty shelf, despite a bin sitting properly on the shelf. This occurred because the line sensor in the front of the robot detected that the robot had gone past the line underneath the shelf. This improper detection was not an issue with the other bins, and is likely due to the human error associated with the placement of the shelf and subsequently the tape underneath the shelves. To address this issue, the team recommends that upon installation, the shelves are bolted down so that they can not move around as the robot is placing or removing bins. Once the shelves are bolted down, the tape should be placed under the shelves at a set distance (depending on the line sensor placement on the robot) and perfectly straight. Alternatively, future work can use other methods such as adding a back wall to the shelf in conjunction with an ultrasonic sensor, to make sure that the bin is properly placed back on the shelf, as well as reducing the likelihood of detecting a missing bin when one does exist on the shelf.

A full table of the results for this test can be found in Appendices F and G.

4.7 Risk Assessment

The team identified the following risks that could occur in the future from our test results and created plans to mitigates these risks.

1. The cleat mechanism does not consistently hook into and lift the bin off of the shelf due to alignment problems. Dealing with this risk is the responsibility of the future design team. The grabbing mechanism should be redesigned or use sensors for better alignment.

2. The line follower and state machine miss detecting a feature identifying a line in the world. Although this did not occur during testing, it is possible after extended use of the system. Dealing with this risk is the responsibility of the system maintainer who needs to ensure the lines on the floor are properly maintained over time as to not fade or be damaged. The necessity of keeping floor lines in good condition will be made clear to the system maintainer.

3. The robot is unable to turn accurately and/or drive straight. Dealing with this risk is the responsibility of the future design team. This problem occurred occasionally during testing while the robot was moving a heavy payload. This risk can be reduced by tuning the PID values of the robot's motion so that turns are always completed correctly.

4. The robot loses WiFi connection. Dealing with this risk is the responsibility of the system maintainer. The system maintainer must ensure the room where the robot is operating has an adequate WiFi connection so that the robot does not become disconnected.

5. Robot tips over during operation. The team has ensured the robot will not tip over while carrying 4.5kg but the robot could tip over if it runs over obstacles.

It is the responsibility of the system maintainer to ensure the work-space is clear of obstacles and that the bins do not exceed the weight limit.

6. Local Inventory files become corrupt or are lost. Dealing with this risk is the responsibility of the system maintainer. The GUI saves this data locally on the computer it is being run on. The system maintainer will need to back up this data or at least ensure the computer is in good condition and will not have storage malfunctions that could corrupt or delete the data.

7. User takes more parts than indicated. Dealing with this risk is the responsibility of the system maintainer. The system maintainer will need to communicate the intended use of the system to all users and may also want to set up a surveillance system to track who has taken more parts than indicated in the borrowed parts inventory. Or the system maintainer could choose to accept this loss and replace the parts.

8. Inventory is incorrectly entered by a system maintainer. Dealing with this risk is the responsibility of the system maintainer. The system maintainer will need to train all staff on how to enter inventory into the JSON file or create an inventory editor application for easier use. Routine inventory checking may also be necessary to reduce this risk.

9. User or system maintainer contaminate parts bin with germs. Dealing with this risk is the responsibility of the system maintainer. The system maintainer should communicate proper sanitation protocols to users of the system and should provide cleaning materials such as hand sanitizer or disposable gloves for handling parts in the bin. If a disease outbreak is traced back to this system, it must be shut down to allow for all germs to become inactive. Stricter

sanitation protocols should be added and/or the system should be modified to include a self-sanitization method.

These risks are summarized in Table 4.1. The columns in the table from left to right are the risk, the consequence of the risk, the probability of the risk occurring, what causes the risk, the person responsible for the risk management, the mitigation plan before the occurrence, and the plan to manage the risk after the occurrence.

Table 4.1: Risk Assessment Table

Risk	**Cons.**	**P**	**Cause**	**Owner**	**R(P)**	**R(A)**
Poor Cleat/ lift mechanism reliability	Bin contents spilled, parts not delivered to user, property damage	Med	System use	Future Design Team	Implement auto-retry on procurement and system testing	Redesign of cleat mechanism, additional sensors
Poor Line follower reliability	Robot does not navigate correctly, may hit something in warehouse	Low	System use	Future Design Team	System testing, line follower calibration, and clean working environment	System testing and redesign navigation
Poor turning reliability	Robot does not navigate correctly, may hit something in warehouse	Low	Improperly tuned turning PID values	Future Design Team	Implement time-out with safe-stop in the event that setpoint is not reached.	System testing and use additional sensors
Loss of WiFI connection	Robot is unable to receive commands from the GUI	Low	Router turns off/ WiFi chip on robot malfunctions	System Maintainer	System Maintainer ensures WiFi is adequate or robots so that they do not become disconnected	System Maintainer ensures WiFi is adequate for robots so that they do not become disconnected
Robot tips over during use	System requires human correction. Possible damage of property	Low	Obstacle or very heavy bin in workspace	System Maintainer	Ensure workspace is clear of obstacles, ensure bins are correctly filled	System Maintainer resets/repairs system

Table 4.1 continued from previous page

Risk	Cons.	P	Cause	Owner	R(P)	R(A)
Dataloss in inventory files	Inventory information and log of borrowed parts is lost	Low	Computer malfunction	System Maintainer	Back up inventory and make sure computer is healthy	Restore from backup, assume some losses, change to remote storage solution
User takes more parts than indicated	Inventory becomes inaccurate and possible loss of property	Med	User has intent to steal or makes mistake	System Maintainer	Assume loss will occur	Set up surveillance, add system features to mitigate this problem
Error with inventory entry	Inventory is incorrect, user may not receive the parts they requested	Low	System Maintainer makes mistake	System Maintainer	Check Inventory is correct	Correct inventory
Bin contamination	Disease transmission	Med	User does not follow sanitation protocols	System Maintainer	Provide sanitation items for user and remind them of protocols	Shut down use of system, increase sanitation requirements, or add active sanitation to system

Chapter 5

Discussion and Future Work

At the conclusion of the semester, all requirements were met, and the system had shown promise. However, the team has certain recommendations for system improvements, as well as directions for future work of the project.

5.1 System Improvements

5.1.1 Structural Improvements

One of the requirements met by the team was to be able to lift and transport the maximum capacity of the bin, 4.5kg. Although this requirement was met, it quickly became clear that to improve the lifespan of this robot, as well as potentially lift more weight in the future, the robot should be made from more durable materials. The current implementation uses quarter-inch plywood for the mobile base, as well as Polylactic-acid (PLA) for the 3D-printed components. These materials do not provide the mechanical rigidity needed for heavier loads in the current Base Bot design, as the structure of the Base Bot deforms from the stresses of holding the weight. The team suggests machining the mobile base from stronger materials, like aluminum, or redesigning the Base Bot such that the structure is rigid enough to prevent flexion using PLA and plywood.

5.1.2 Lift Improvements

In our proof-of-concept lifter design, the robot can access two shelves high. However, in future implementations of this system, the lift mechanism should be made taller to access more shelves to make better use of vertical space in the storage rooms. Two approaches could be taken to accommodate this. The first is to purchase a longer lead screw and linear motion rods, as well as make the necessary structural changes to support this change. The alternative approach would be to redesign the lift mechanism. The latter may prove difficult due to torque requirements and making the system resistant to back-drive.

5.1.3 Auto-Charge

During the testing and development process, the team noticed how quickly the 12-volt battery on the robot would discharge. After about one hour of testing, which consisted of navigation, procurement, return, and parking, the robot's battery was approximately about 50% discharged. Battery life of about 2 hours is not sufficient for the system to run throughout the day so future design iterations should develop an automatic battery recharging feature. The team proposes using additional circuitry which can detect the voltage of the power rails and when the voltage drops below a certain threshold, the firmware should command the robot to park itself. The robot base should be redesigned such that it allows the robot to be charged via metal contacts, an inductive charging pad similar to inductive chargers present in smartphones, or some other charging port. The parking spot would also be outfitted with corresponding metal contacts, an inductive charging pad, or a port which the robot must align with so that the robot can charge itself in between procurement sessions. These firmware and hardware changes would allow the robot to determine when its battery is critically low, and take action to recharge it.

5.1.4 Bin Alignment

Currently, the robot can align with the bins on the shelf by line-following up to them slowly. To reduce the risk of misalignment, the robot attempts to procure a bin five times before giving up. This means that if a bin is slightly misaligned, then the robot will drop the bin, correct itself, and retry to align. Although this works well and is simple to implement, the team recommends using AprilTag fiducials [10] on each of the bins, in conjunction with a camera. As it approaches the bin, the robot could adjust its heading to keep the camera centered on the AprilTag, which would align the cleat with the bin and increase the reliability of the system. This, in conjunction with the multiple retry method, should greatly reduce the number of unsuccessful bin procurements.

5.1.5 Navigation Improvements

In this proof-of-concept, the robot 'localizes' itself simply by being given a starting position and orientation, and determines its position as it's moving by counting column and row markers indicated by black electrical tape on the floor. Since the environment for the full implementation of this robot is well structured, there is little risk of the tape being damaged enough to cause the robot to fail to localize. This has worked well for this proof-of-concept but if it were to miss a row or column marker, it would not be able to correct its position. Some of the risks of missing row and column markers can be reduced by keeping the light in the work area constant or by using an automated calibration routine to train the robot to detect the color difference between the lines and the rest of the floor. In this routine, the robot could drive around to find the sensor readings from the lines and the rest of the ground and write those readings to variables used for navigation. This calibration would allow the robot to function the same way in environments with different lighting conditions, without manual re-calibration. Alternatively, other localization methods could be used instead of line-following that would make the localization more robust and reliable such as Simultaneous Localization and Mapping (SLAM).

5.2 Future Directions

5.2.1 Integration with Odoo

As mentioned in the introduction section of this report, RBE students use Odoo in the process of procuring components for their classes. Odoo is responsible for billing the students for components not returned, as well as keeping track of inventory. This current implementation does not use Odoo and instead focuses on the robotic aspect of the project. Future improvements should develop a link between the GUI developed in this project, and Odoo so that Odoo performs all the inventory tracking. Storing the inventory data remotely using Odoo as opposed to locally on one machine, eliminates the risk of losing the inventory data if the local machine were to malfunction. This also allows the inventory information to be stored only in one place, removing the risk of having multiple copies of the inventory with conflicting information. The GUI uses a JSON file, which contains the locations, names, and stock amount of the robotics components available in the system. One possible approach the team proposes is to add functionality to Odoo that generates a JSON file containing the inventory that is available for the robot to procure and send it to the GUI whenever the GUI requests this information. This request would be made every time a new student starts a session so that the latest inventory is always displayed. The GUI would also need to be able to send the JSON file back to ODOO containing the changes to the inventory and information of who borrowed the components.

5.2.2 Inventory Tracking

All inventory management in this current implementation was done using the “honor-system”. In this proof-of-concept, there is no way to verify how many components were actually taken from the bin by a student. One possible solution is to use a scale, which would be part of the procurement process. The robot could bring the bin over to the scale and weigh it before bringing it over to the user and then using the known weight of each component in the bin determine the number of components inside the bin. When the student is finished taking components, the robot brings the bin back to the scale, weighs the bin, determines the number of components corresponding to the new weight, and then calculates the difference to find the number of components that the user has borrowed.

Another benefit of a scale would be to use the weight measurements in some mathematical function to determine proper PID gains for the navigation and lift mechanism. The results had shown that the robot occasionally struggled to lift a bin to a proper height and occasionally was unable to complete a turn so increasing the gains in the presence of more weight would increase the reliability of the system.

5.2.3 WPI ID Card Reader Integration

When using the GUI for requesting components, the student must manually enter their student ID number. However, WPI has card readers that are used at events and more recently COVID-19 testing, that automatically determine the student

ID number. The team recommends that software be written to integrate the card readers used by WPI into the existing GUI, allowing students to quickly swipe their ID instead of manually entering the ID number. This also reduces the possibility of human error when entering the ID number.

5.2.4 Autonomous Sanitation

As mentioned previously, this project was performed during the COVID-19 pandemic and part of its motivation was to remove the human-to-human contact when borrowing components. However, with students reaching their hands into bins, there is a risk that components left in the bin could be contaminated and infect a future user. To prevent this, some form of automated sanitation should be considered in between procurement sessions. The team explored the use of disinfecting the bins using UV-C light, which is capable of disinfecting surfaces [11]. Each bin bay would have its own light that is turned on for a set period after a bin has been returned into the bin bay. This would allow each bin to be sanitized at the same time if necessary. Ultimately this was not pursued because ensuring all components and surfaces inside the bin are sanitized would require more resources than the team had available.

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Appendix A

Lab Staff Survey Questions

1. How long have you been a Lab Assistant?
   (a) Under 1 year
   (b) 1 year
   (c) 2+ years
2. Can you briefly describe your responsibilities as a Lab Assistant? Short Answer
3. Can you briefly describe the process that students have to follow to request parts/parts through Odoo? Short Answer
4. What is your role in the process? Short Answer
5. What parts/parts are typically most requested? Short Answer
6. At the end of the term, what parts are students expected to return? Short Answer
7. At the end of the term, what parts are students allowed to keep? Short Answer

8. If any parts are returned:
   (a) What is the process for students to return parts/parts? Do they need to drop these parts somewhere? Long Answer
   (b) Are parts/parts made available for other students to use?
      i. Yes
      ii. No
      iii. No parts returned
   (c) Are parts/parts inspected after they are returned?
      i. Yes
      ii. No
      iii. No parts returned
   (d) Are parts/parts cleaned or sanitized after they are returned?
      i. Yes
      ii. No
      iii. No parts returned
9. How many times are you asked to retrieve parts per hour during peak times of the term?
   (a) Less than once per hour
   (b) Once an hour
   (c) 2-3 times per hour
   (d) 4 or more times per hour
   (e) Other __

10. Are parts cleaned after they are returned in the current system? If so, how? Short Answer

11. How long does it take you to service a request from the moment it is made? Short Answer

12. I find it difficult to keep up with the volume of requests; Select within range:

    (a) 1 Strongly Disagree

    (b) 5 Strongly Agree

13. What part of the process do you enjoy the most? Short Answer

14. What part of the process do you least enjoy? Short Answer

Appendix B

Student Survey Questions

1. What is your major? Select all that apply:
   (a) ECE
   (b) RBE
   (c) ME
   (d) CS
2. What classes have you taken so far? Select all that apply:
   (a) RBE 1001
   (b) RBE 2001
   (c) RBE 2002
   (d) RBE 3001
   (e) RBE 3002
   (f) Other __
3. Do you live _ ?:

(a) On-campus

(b) Off-campus

4. If off-campus, within what distance do you live from campus?

   (a) 10 miles

   (b) 50 miles

   (c) 100+ miles

   (d) I live on-campus

   (e) Other __

5. So far this semester, how many parts/parts have you requested through Odoo? Short Answer

6. What kinds of parts do you typically request? Short Answer

7. How many parts do you usually request on average at one time? Short Answer

8. Considering other RBE classes you have taken in the past, how many parts do you typically request through Odoo? (If you're currently taking your first RBE course, type N/A). Short Answer

9. I am satisfied with the way parts are currently acquired at WPI: Select within range.

   (a) 1 Strongly Disagree

   (b) 5 Strongly Agree

10. Can you please describe the process you have to follow to request parts through Odoo?

11. What is the longest time you typically wait to receive the part after requesting it?

    (a) Under an hour

    (b) 1-3 hours

    (c) 4-8 hours

    (d) 1-2 days

    (e) more than 2 days

12. The delay in receiving parts hinders my ability to do well on the final project: Select within range.

    (a) 1 Strongly Disagree

    (b) 5 Strongly Agree

13. I am satisfied with the time it takes to get my parts: Select within range.

    (a) 1 Strongly Disagree

    (b) 5 Strongly Agree

14. If you could name one thing that you would like to change about the current process, what would that be? Short answer

Appendix C

Bill of Materials

Part Name	**Total Quantity**	**Unit Cost**	**Total Cost**	**Supplier**
		Frame		
PLA (1000g) Roll	2	$25.00	**$50.00**	Amazon
Plywood Plates*	2	$0.00	**$0.00**	RBE Lab
Standoff*	2	$0.00	**$0.00**	RBE Lab
Hinge Lower*	2	$0.00	**$0.00**	RBE Lab
Hinge Upper*	2	$0.00	**$0.00**	RBE Lab
M5 Thread Inserts	26	$0.25	**$6.50**	Odoo
Battery Holder*	1	$0.00	**$0.00**	RBE Lab
		Electronics		
12 Volt Acid Battery	1	$13.99	**$13.99**	Odoo
H-Bridge	3	$17.95	**$53.85**	Odoo
Logic Level Converter	3	$2.95	**$8.85**	Odoo
Robot Interface Module	1	$36.85	**$36.85**	Odoo

Continued from previous page

Part Name	Total Quantity	Unit Cost	Total Cost	Supplier
IMU	1	$34.95	**$34.95**	Odoo
Line Follower	2	$9.95	**$19.90**	Pololu
Wheels				
Wheel bracket*	2	$0.00	**$0.00**	RBE Lab
Wheel*	2	$0.00	**$0.00**	RBE Lab
Drive Gear	2	$0.00	**$0.00**	RBE Lab
50:1 12V 37D Motor Enc.	2	$35.95	**$71.90**	Pololu
Lifter				
Support Truss**	2	$0.00	**$0.00**	None
Motor Holder**	1	$0.00	**$0.00**	None
Top Truss Support**	1	$0.00	**$0.00**	None
Bottom Support**	1	$0.00	**$0.00**	None
10mm 300mm ACME Screw	1	$15.99	**$15.99**	Amazon
Steel Linear Motion Rod	2	$11.39	**$22.78**	Amazon
6mm to 10mm Shaft Coupler	1	$12.99	**$12.99**	Amazon
6.3:1 12V 37D Motor w/ Enc.	1	$39.95	**$39.95**	Pololu
Optical Limit Switch	2	$0.99	**$1.98**	Amazon
Cleat Assembly				

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Part Name	**Total Quantity**	**Unit Cost**	**Total Cost**	**Supplier**
Lift Platform**	1	$0.00	**$0.00**	None
Linear Ball Bearing (2 pack)	1	$10.29	**$10.29**	Amazon
10mm Threaded Nut	1	$0.00	**$0.00**	Amazon
Button Limit Switch	1	$0.70	**$0.70**	Amazon
Attachable Cleat**	1	$0.00	**$0.00**	None

- * Part was supplied by the RBE Foisie Lab Manager and cost is unknown.
- ** Part was designed and printed by the team using the the 1000g PLA rolls

Appendix D

Lift Results Data

Load(kg)	Command(mm)	Achieved(mm)	Error(mm)
0	131.68	131.13	-0.55
0	131.68	132.41	0.73
0	131.68	131.22	-0.46
0	131.68	132.12	0.44
0	131.68	131.57	0.89
0	131.68	131.13	-0.55
0	131.68	131.34	-0.34
0	131.68	131.86	0.18
0	131.68	131.57	-0.11
0	131.68	132.15	0.47
1	131.68	131.17	-0.51
1	131.68	132.67	0.99
1	131.68	132.47	0.79
1	131.68	131.96	0.28

Continued on next page

Table D.1 – continued from previous page

Load(kg)	Command(mm)	Achieved(mm)	Error(mm)
1	131.68	131.98	0.3
1	131.68	131.82	0.14
1	131.68	132.54	0.86
1	131.68	130.84	-0.84
1	131.68	130.89	-0.79
1	131.68	130.01	0.33
2	131.68	132.01	0.60
2	131.68	132.28	0.85
2	131.68	132.53	0.85
2	131.68	132.18	0.50
2	131.68	131.77	0.09
2	131.68	132.51	0.83
2	131.68	131.18	-0.5
2	131.68	130.21	-1.47
2	131.68	131.93	0.25
2	131.68	131.73	0.05
2	131.68	130.69	-0.99

Appendix E

Navigation Test Results

Load(kg)	Command([x,y])	Achieved?
0	[2,-3]	Y
0	[1,-3]	Y
0	[2,-3]	Y
0	[1,-3]	Y
0	[2,-3]	Y
0	[1,-3]	Y
0	[2,-3]	Y
0	[1,-3]	Y
0	[2,-3]	Y
0	[1,-3]	Y
1	[2,-3]	Y
1	[1,-3]	Y
1	[2,-3]	Y

Continued on next page

Table E.1 – continued from previous page

Load(kg)	**Command([x,y])**	**Achieved?**
1	[1,-3]	Y
1	[2,-3]	Y
1	[1,-3]	Y
1	[2,-3]	Y
1	[1,-3]	Y
1	[2,-3]	Y
1	[1,-3]	Y
2	[2,-3]	Y
2	[1,-3]	Y
2	[2,-3]	Y
2	[1,-3]	Y
2	[2,-3]	Y
2	[1,-3]	Y
2	[2,-3]	Y
2	[1,-3]	Y
2	[2,-3]	Y
2	[1,-3]	Y

Appendix F

Procurement Results Data

Load(kg)	Procured?	Time(s)
0	Y	41.85
0	Y	40.63
0	Y	40.89
0	Y	41.51
0	Y	41.05
0	Y	41.21
0	Y	46.61
0	Y	39.64
0	Y	45.06
0	Y	43.70
1	Y	48.12
1	Y	46.60
1	Y	46.97
1	Y	48.51

Continued on next page

Table F.1 – continued from previous page

Load(kg)	Procured?	Time(s)
1	Y	46.68
1	Y	N/A
1	Y	44.65
1	Y	N/A
1	Y	47.05
1	Y	N/A
2	Y	44.36
2	Y	47.18
2	Y	44.57
2	Y	45.66
2	Y	43.49
2	Y	45.36
2	Y	43.64
2	Y	43.57
2	Y	44.33
2	Y	45.05

Appendix G

Return Results Data

Load(kg)	Returned?	Time(s)	Total(s)	Parked?
0	Y	29.88	71.73	Y
0	Y	29.82	70.45	Y
0	Y	30.04	70.93	Y
0	Y	28.98	69.49	Y
0	Y	29.03	70.08	Y
0	Y	29.63	70.84	Y
0	Y	32.83	79.44	Y
0	Y	29.03	68.67	Y
0	Y	29.84	74.9	Y
0	Y	29.89	73.59	Y
1	Y	34.57	82.69	Y
1	Y	34.58	81.18	Y
1	Y	33.50	80.47	Y
1	Y	33.78	82.29	Y

Continued on next page

Table G.1 – continued from previous page

Load(kg)	Returned?	Time(s)	Total(s)	Parked?
1	Y	34.83	81.51	Y
1	Y	N/A	N/A	N/A
1	Y	34.34	78.99	Y
1	Y	N/A	N/A	N/A
1	Y	33.61	80.66	Y
1	Y	N/A	N/A	N/A
2	Y	33.11	77.47	Y
2	Y	34.01	81.19	Y
2	Y	33.35	77.92	Y
2	Y	33.91	79.57	Y
2	Y	33.60	77.09	Y
2	Y	34.08	79.44	Y
2	Y	33.70	77.34	Y
2	Y	33.67	77.24	Y
2	Y	33.95	78.28	Y
2	Y	33.75	78.80	Y