Wrench Monkey

GROUP 9

William Wandelt
Electrical Engineering

Rachael Sak
Electrical Engineering

Matthew Crespo
Electrical Engineering

Matthew Trump
Computer Engineering

Reviewers

Professor Maddox
Dr. Aman Behal
Dr. Mike Borowczak

Figure List......5
Table List......6
Image List......7
Chapter 1: Executive Summary......1
Chapter 2: Project Description......3
Section 2.1: Background and Motivation......3
Section 2.2: Past Work......4
Section 2.3: Goals and Objectives......6
Section 2.4: Features and Functionalities......7
Section 2.5: Engineering Specifications......8
Section 2.6: Hardware Block Diagram......10
Section 2.7: Software Flow Chart......11
Section 2.8: Prototype Illustration......12
Section 2.9: House of Quality......13
Chapter 3: Research and Part Selection......14
Section 3.1: Control System Research......14
Section 3.1.1: Bang-bang Control......14
Section 3.1.2: Proportional - Integral - Derivative Control......15
Section 3.1.3: Model Predictive Control......15
Section 3.1.4: Reinforcement Learning (RL)......16
Section 3.1.5: Control System Comparison and Selection......17
Section 3.2: Mobile Application & Desktop Website......17
Section 3.2.1: LAMP Stack......18
Section 3.2.2: MERN Stack......19
Section 3.2.3: Stack Comparison and Selection......20
Section 3.3: Motors......21
Section 3.3.1: Brushed DC Motors......21
Section 3.3.2: Brushless DC Motors......22
Section 3.3.3: Stepper Motors......23
Section 3.3.4: Servo Motors......24
Section 3.3.5: Motor Comparison and Selection......25
Section 3.4: Tool Detection Sensors......26
Section 3.4.1: Resistive Strain Gauge......26
Section 3.4.2: Capacitive Load Cell Detection......27
Section 3.4.3: Photoelectric Detection......28
Section 3.4.4: RFID Detection......29
Section 3.4.5: Tool Detection Sensor Comparison and Selection......30
Section 3.5: Batteries......31

Section 3.5.1: Lithium Ion Battery.. 31
Section 3.5.2: Sealed Lead Acid (SLA) Battery.. 32
Section 3.5.3: Nickel-Cadmium Battery.. 33
Section 3.5.4: Battery Comparison and Selection...33
Section 3.6: Line Detection Sensors...35
Section 3.6.1: Color Sensor.. 35
Section 3.6.2: Camera Sensor..36
Section 3.6.3: IR Sensor.. 36
Section 3.6.4: Line Detector Sensor Comparison and Selection......................... 37
Section 3.7: Chassis Base Material.. 39
Section 3.7.1: Wood...39
Section 3.7.2: Aluminum... 40
Section 3.7.3: Plastic...41
Section 3.7.4: Carbon Fiber.. 41
Section 3.7.5: Chassis Base Material Comparison and Selection....................... 42
Section 3.8: Microcontrollers & Single-Board Computers...43
Section 3.8.1: ESP-32S.. 44
Section 3.8.2: Raspberry Pi 4B...44
Section 3.8.3: Arduino Uno R4 WiFi.. 45
Section 3.8.4: Microcontroller Comparison and Selection.................................. 46
Section 3.9: Part Selection...46
Section 3.9.1: Chassis Material...47
Section 3.9.2: Battery Type...48
Section 3.9.3: Motor Type... 50
Section 3.9.4: Line Detector Sensor.. 52
Section 3.9.5: Tool Detection Sensor...53
Section 3.9.6: Control Processor Selection...54
Chapter 4: Design Standards and Constraints... 57
Section 4.1: Project Standards.. 57
Section 4.1.1: Soldering Standard.. 58
Section 4.1.2: Wi-Fi Standard... 59
Section 4.1.3: Industrial Mobile Robots Standard..60
Section 4.1.4: PCB Design Standard...60
Section 4.1.5: LED Standard...61
Section 4.1.6: C Programming Language Standard... 61
Section 4.1.7: Inter-Integrated Circuit (I2C).. 61
Section 4.1.8: Portable and Rechargeable Batteries Standards..........................62
Section 4.2: Project Constraints...62
Section 4.2.1: Economic Constraints... 62
Section 4.2.2: Time Constraints... 63
Section 4.2.3: Availability Constraints... 64

Section 4.2.4: Safety Constraints....65
Section 4.2.5: Size and Weight Constraints....65
Section 4.2.6: Testing Constraints....66
Section 4.2.7: Environmental Constraints....66
Section 4.2.8: Technical Constraints....67
Section 4.2.9: Usability Constraints.... 67
Chapter 5: Comparison of Chat GPT with Other Similar Platforms.... 68
Section 5.1: Chat GPT and Other Similar Products.... 68
Section 5.1.1: A History and Comparison of Chatbots....69
Section 5.2: Chat GPT in Education....70
Section 5.2.1: Benefits of Chat GPT in Senior Design....70
Section 5.2.2: Drawbacks of Chat GPT in Senior Design....72
Section 5.2.3: Conclusion.... 73
Chapter 6: Hardware Design....75
Section 6.1: Tool Detection.... 75
Section 6.1.1: Pressure Sensors....76
Section 6.1.2: RFID....77
Section 6.2: Power Distribution....78
Section 6.3: Motor Control System.... 79
Section 6.4: Ultrasonic Collision Avoidance....80
Section 6.5: Line Detection.... 81
Section 6.6: Custom PCB.... 81
Chapter 7: Software Development.... 84
Section 7.1: MERN Stack Development.... 84
Section 7.1.1: Database Contents.... 84
Section 7.1.2: Desktop Website Development....86
Section 7.1.3: Mobile Application Development....91
Section 7.1.4: Hosting.... 94
Section 7.2: Arduino IDE....96
Section 7.2.1: Movement.... 97
Section 7.2.2: Line Following.... 99
Section 7.2.3: Tool Detection: Pressure Sensor....100
Section 7.2.4: Tool Detection: RFID....101
Chapter 8: System Fabrication and Assembly....102
8.1: Main Control Board.... 102
8.2 Custom Hardware.... 104
8.2.1 Motor Mounts.... 104
8.2.2 RFID Mount....104
8.2.3 Infrared Sensor Array Mount....105
8.2.4 PCB Enclosure....105

8.3 Project Assembly.. 106
8.3.1 Chassis Assembly..106
8.3.2 Tool Detection System Assembly...106
8.3.3 Overall System Assembly... 107
Chapter 9: System Testing and Evaluation.. 108
Section 9.1: Line Following.. 108
Section 9.2: Transportation with Load..110
Section 9.3: Tool Detection..112
Section 9.3.1: Tool Detection: Pressure Sensor...113
Section 9.3.2: Tool Detection: RFID.. 113
Section 9.4: Sending Commands to ESP32 via Website..114
Section 9.5: Senior Design 2..115
Chapter 10: Administrative Content...116
Section 10.1: Budget and Financing... 116
Section 10.2: Bill of Materials...117
Section 10.3: Project Milestones for Senior Design 1 and Senior Design 2............ 118
Section 10.4: Work Distribution...120
Section 10.4.1: Team Leader... 121
Section 10.4.2: Discord/Group Chat... 121
Section 10.4.3: Estimated Table of Work Distributions...................................... 121
Section 10.5: User Manual..122
Section 10.5.1: Creating an Account...122
Section 10.5.1: Using an Admin Account..123
Section 10.5.1.1: Creating and Editing Tools.. 123
Section 10.5.1.2: Creating and Editing Jobs... 123
Section 10.5.1: Using a Standard Users Account.. 124
Section 10.5.1.2: Calling to a Workstation.. 125
Section 10.5.1.2: Checking Out Tools... 125
Section 10.5.1.2: Checking Out Jobs...126
Section 10.5.1.2: Checking In Tools...126
Section 10.5.2: Setting up the Track... 127
Chapter 11: Conclusion...128
Appendix A... i

Figure List

Figure 1: Hardware Block Diagram ………………………………………………....10
Figure 2: Software Block Diagram ………………………………………………..11
Figure 3: Several prototype sketches showing components and sizes …………12
Figure 4: House of Quality …………………………………………………………...13

Table List

Table 1: Engineering Specifications ……………………………………………………..8
Table 2: Control System Comparison ………………………………………………17
Table 3: Stack Comparison ..…………………………….…………………………..21
Table 4: Motor Properties Comparison …………………………………………….26
Table 5: Tool Detection Sensors Comparison ……………………………………...31
Table 6: Battery Comparison ………………………………………………………...34
Table 7: Line Detection Sensor Comparison………………………..………...39
Table 8: Chassis Base Material Comparison………………………..………...43
Table 9: Microcontroller & Single-Board Computer Selection……………………46
Table 10: Wood Selection…………………..………………………………….…....48
Table 11: Battery Selection……………………..…………………………………50
Table 12: Motor Selection……………………..……………………………….......52
Table 13: Line Sensor Detection Selection……………..……………………..…...53
Table 14: Tool Detection Selection………………………………………......…....54
Table 15: Microcontroller & Single-Board Computer Selection……...……...…..55
Table 16: Estimated Budget……………………………………….…………….....116
Table 17: Bill of Materials ………………………………………………..……117
Table 18: Research and Writing Milestones……………………………..………118
Table 19: Design and Prototype Milestones………………...………..…..…....119
Table 20: Work Distribution ………………………………….………………...121

Image List

Image 1.1: Wrench Monkey ……………………………………………………….2
Image 3.1: Plywood Board Used …………………………………………………48
Image 3.2: HWE Energy Battery Used ……………………………….……50
Image 3.3: Selected Servo Motors for Wrench Monkey …………………….…51
Image 3.4: IR Sensor Used ……………………………..………………...…53
Image 3.5: RFID Reader and Thin Film Strain Gauge …………………...……54
Image 3.6: ESP-32S Module Chosen ……………………………………....55
Image 6.1: Tool Detection Block Diagram ………………………………..…..76
Image 6.2: Toolbox Tray Insert ……………………………………………...……78
Image 6.3: Power Distribution Board Block Diagram ……………………..………79
Image 6.4: Control System Signal Flow Diagram ……………………………..…..82
Image 6.5: PCB Schematic ………………………………………………………..…83
Image 7.1: MongoDB data structure diagram …………………………….…..86
Image 7.2: Figma Prototype of Register, Login, and Manager Page………..…..87
Image 7.3: User Dashboard Screen ……………………………...……………89
Image 7.4: Website Use Case Diagram.………….. …………………………..……90
Image 7.5: Mobile Application Login and Home Page (robot is traveling).....…..92
Image 7.6: Class Diagram of Mobile Application……………………………….93
Image 7.7: Data Transfer Diagram (Atlas to Websocket to ESP32)......………...96
Image 7.8: State Diagram for Basic Movement……………………………………98
Image 8.1: Custom PCB …………………………………………………………103
Image 8.2: Motor Mount to Chassis………………………………………………104
Image 8.3: RFID Mount to Chassis………………………………………….…105
Image 8.4: IR Array Mount to Chassis…………………………………..……….105
Image 8.5: PCB Enclosure Mount to Toolbox……………………………………106
Image 9.1: IR Sensor ……………………………………………………….……109
Image 9.2: Initial Motor Testing ………………………………………………….111
Image 9.3: Second Motor Test ………………………………………………….…112
Image 9.4: Tool Detection Component Testing ……………………………..……114
Image 10.1: Website Registration Page………...…………………………………121
Image 10.2: Admin Account Dashboard……………………………...…………123
Image 10.3: Add Tool Screen…………………………………………………….123
Image 10.4: New Job Prompt………………………………………………....124
Figure 10.5: Standard User Account Dashboard…………………………………124
Figure 10.6: Requesting a Station…………………………………………………125
Figure 10.7: Checking Out Tools…………………………………………………125
Image 10.8: Job Checkout…………………………………………………...…126
Image 10.9: Job Checkout Confirmation……………………………………..126
Image 10.10: Checking in Tools…………………………………………….…127
Image 10.11: Printed Line-Following Path…………………………………..…..127

Chapter 1: Executive Summary

In modern industrial environments, the integration of autonomous and semi-autonomous robots has contributed significantly to advancement in operational efficiency and production speed. These robots act like assistants, helping with tasks that would otherwise require a lot of time and effort from human workers. By taking on roles such as tool distribution and retrieval, these tools can free up time to allow workers to focus on the tasks at hand, which increases efficiency. This shift not only boosts productivity but also improves overall workplace satisfaction by simplifying the production process.

Particularly, the utilization of such robots for tool distribution and retrieval stands as an innovative application, which can streamline workflow processes and increase productivity within manufacturing facilities. Common situations, such as a busy factory floor where workers are constantly moving between workstations to fetch tools would be dramatically improved. Otherwise, it's a time-consuming process that can lead to delays and other inefficiencies. With semi-autonomous robots handling this task, tools can be delivered promptly and accurately, and ensures that workers have what they need exactly when they need it. This seamless integration of technology into the workflow not only saves time but also minimizes disruptions, allowing manufacturing and assembly operations to run smoothly.

Our project aims to create a smart robot system that's ideal for moving tools around different workstations in an industrial application. It is capable of moving smoothly and accurately, easily finding its way around to deliver tools where they're needed in the factory. Our aim in automating this part of manufacturing is to make things run smoothly and get as much work done as possible for a given block of time.

This system implements a simple program of automation, navigating its surroundings via a marked line track on the ground to deliver requested tools promptly. The sophistication of the system lies in its ability to adapt to changing conditions on the ground. It can avoid obstacles and communicate with the user to notify of any issues that occur. This level of automation not only reduces the need for human intervention but also minimizes the risk of errors or accidents, creating a safer and more efficient working environment. As shown in *Image 1.1*, the design of our robot, named the Wrench Monkey, is tailored to efficiently navigate and deliver tools across various workstations.

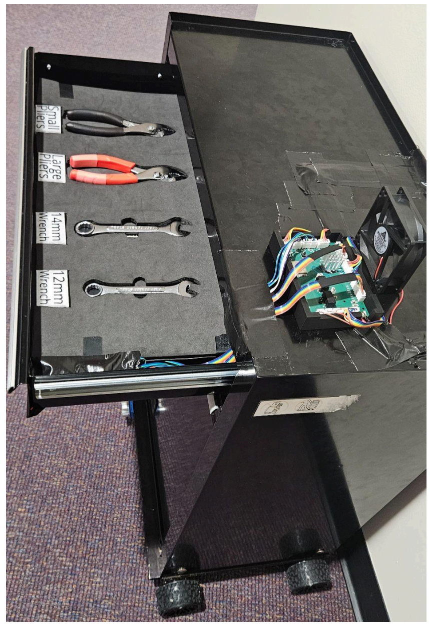

Image 1.1: The Wrench Monkey

Unlike conventional systems, our robot is engineered to service multiple workstations seamlessly, optimizing resource allocation and minimizing downtime. This aspect of our design is crucial for ensuring maximum efficiency in a dynamic manufacturing environment. Instead of being limited to a single workstation, our robot can move between different areas of the floor as needed, servicing multiple users depending on the tools required. This flexibility helps to minimize bottlenecks and ensures that production can continue uninterrupted, even in the face of unexpected challenges.

Central to the functionality of our robotic system is its discernment of tool placement. Through a combination of weight sensing and RFID technology, the robot possesses the capability to identify where tools are placed. This enables it to not only locate requested tools efficiently but also detect and alert users of misplacements. If a tool is detected in the wrong location, the system is designed to alert users visually and through text on the workstation, preventing potential disruptions and ensuring that tools are always readily available when needed.

The significance of such automation lies in its impact on efficiency and resource utilization within industrial settings. By reducing the need for manual tool retrieval and distribution, our robotic system liberates human capital to focus on high-value tasks, thereby enhancing overall productivity and operational agility. This shift in focus from manual labor to more strategic activities helps to unlock the full potential of the workforce, driving innovation and driving the company forward.

Moreover, the centralization of tool management via a web app within a controlled robotic framework facilitates the efficiency gains. By combining tool inventory and distribution under a unified system, redundancies and inefficiencies inherent in manual tracking and management are eliminated. This results in streamlined operations, reduced downtime, and optimized resource allocation.

Implementing our robotic system successfully necessitates consideration of various design parameters. Object collision recognition must work to demonstrate capabilities in line with what would be expected in an industrial setting.. Additionally, robust communication protocols are essential for seamless integration with the control system and accompanying tool status information. These requirements ensure that our system can operate smoothly and effectively in a real-world manufacturing environment, without causing disruptions or delays.

The benefits of an operational system like this are easy to imagine. Beyond immediate gains in operational efficiency, the implementation of semi-autonomous tool-distributing robots promises long-term benefits in terms of scalability and adaptability in the industrial landscape. Modifications can be made using the existing framework to service other industries, such as hospitals for food delivery.

In conclusion, the advent of semi-autonomous robots for tool distribution can create a new era of efficiency and optimization in industrial environments. Through strategic design and implementation, our robotic system will attempt to change the game of workflow management, by facilitating high levels of productivity and operational efficiency. Using the power of automation, a smarter, more efficient factory can be made.

Chapter 2: Project Description

This section outlines the project that is being created, the Wrench Monkey. First, the background and the motivation for completing this project is explained to show why this product was decided upon, as well as any past research and existing work done in this area. Next, the goals and objectives that should be accomplished are listed, as well as the expected features and functionalities that are to be incorporated. Finally, this section includes the hardware and software diagrams, the engineering specifications, the house of quality, and the prototype illustration. The goal of this section is to outline the overall project and provide a clear description of what is being created.

Section 2.1: Background and Motivation

For decades, robots have been used in various industries to automate repetitive tasks and improve overall efficiency. The scope of robotic applications is vast, ranging from precision driven manufacturing of microchips, to the optimization of logistic processes in sorting centers and automated assembly lines streamlining production in various sectors. While the impact of robotic applications have been profound in manufacturing and assembly lines, the potential for robotics in addressing challenges within shared workspaces has yet to be fully explored.

In these specific environments, where seamless collaboration between workers is of utmost importance, the need for effective tool organization has become increasingly apparent. Shared workspaces in fields from manufacturing or repairs to research and development, often take on the issue of disorganization and tool misplacement. The traditional methods of tackling this issue, such as manual tracking of tools through sign out sheets have proven inadequate in the evolving demands of modern work environments. This inadequacy becomes even more apparent as the number of workers within these shared spaces increases, necessitating a new dynamic solution.

Recognizing these challenges, our senior design project uses robotics and automation to address the persistent problem of tool organization in shared workspaces. The focus goes beyond increasing efficiency, extending to the broader challenges of accessibility within said environments. Our innovative solution takes the form of a toolbox robot, designed to seamlessly integrate into collaborative work environments, revolutionizing the way tools are managed.

Wrench Monkey, our envisioned toolbox robot, represents more than just a technical solution, but a leap forward in the evolution of collaborative workspaces. By redefining the dynamics of tool organization, our project aspires to contribute to the modern day workspaces that are not only efficient, but also adaptive, inclusive, and technologically advanced. As shared workspaces continue to evolve, our senior design project stands as a pioneering effort to shape the future through integration of robotics and intelligent automation.

Section 2.2: Past Work

Toolboxes are a staple in every workplace, as well as in many homes. They vary in size and look, however, for the most part they are all similar in that they have very basic features and are solely a way to store tools. When deciding which toolbox to purchase, there are many things to consider such as size, portability, durability, security in the form of a lockable product, and the inclusion or lack of drawers. While standard toolboxes are sufficient for most environments, there are cases where a more technologically advanced toolbox could be beneficial. There are a few companies that have created toolboxes that contain more technologically advanced features; however, these are often not easily accessible to the average consumer.

There are a handful of toolboxes on the market with varying levels of automation and inventory tracking. Most of these products seem to focus on checking out tools to hold employees accountable and prevent the loss of items. One such product is a smart toolbox created by Snap-On in 2012 called the Level 5 ATC Tool Control System. This product was developed for the utility industry and military type settings as a way to track and control access to tools. One benefit listed is that should a tool be left behind somewhere such as inside a jet engine, it could pose not only an extensive amount of damage but also a safety hazard, so having the ability to confirm that all tools have been returned to their designated spot would provide an additional layer of safety. Features included in this toolbox are controlled access to the contents, item tracking and logging, and alert systems for errors.

To even unlock the toolbox, a card has to be scanned, such as an employee ID card. This allows the company to allow only certain people access to the tools. Once the toolbox is unlocked, the user can remove whichever tools they need, and the system has an optional feature where you can log which workspace you will be using the tools in. After closing the drawer, a camera mounted inside the drawer will compare the contents to the control image taken when the toolbox was first programmed and it will list on the touch screen how many tools were taken, where they were removed from, as well as the part numbers. The touch screen also has options to search for specific tools, as well as a way to see who has checked out each tool. When returning the tool, there is a way to notify the system if it is broken or lost, as well as if the tool is out for calibration or needs to be calibrated soon to ensure accuracy. Should a tool be returned to the wrong drawer or spot, the system will alert the user that there is an issue. This tracking and logging system can be very beneficial to users as it helps the users keep everything organized and keep track of tools that are checked out by other users.

Another toolbox on the market is the RFID Smart Toolbox. This device was created by Rovinj Technology, and it uses tools that have RFID tags on them in order to register if the tool is in the toolbox or not. This product has an inventory feature that will alert the individual taking inventory of what tools are missing within 3 seconds. It can also alert users if there is a tool that has not been returned in the allotted time, and will also then identify which person has said tool. A unique feature about this device is that it is smaller than the previously mentioned tool chest and is also rechargeable such that it can be physically taken to a workstation as opposed to being large and stationary, requiring the users to come to it to check out and return items.

The company Tool Raptors has also created a smart toolbox. Their product has four different operating modes, allowing the user to customize it to best suit their needs. The most basic mode is smart access only, which restricts who can unlock and access this toolbox. Another mode adds manual tool tracking where the user would tell the system which item they have taken. There is also the option to use RFID or sensors in order to automatically track which tools are taken and missing from the toolbox. This allows the user to customize the toolbox to best fit their needs. The toolbox is also equipped with a touchscreen and will send an alert when there is unauthorized access, as well as keep a log of who attempts to access the system.

Tramontina also has their own Smart Tool Cabinet, which is equipped with similar features to the others such as a touchscreen and restricted access, requiring a keycard to access the tools. It also uses a digital scanning system in order to track which tools are present in the toolbox. One thing that makes this product unique is the fact that it will automatically open and close the drawers the user needs.

Another such example comes from the Olpin Group's motorized toolbox product. This toolbox is specifically designed to transport tools through a workshop, a feature that aligns with our objective of semi-autonomously moving a toolbox through a workshop's space.

One of the safety features of the Olpin Group's toolbox is also relevant to our project. The built-in emergency stop feature ensures safety of users in the immediate serviceable area. This feature is similar to our project's implementation of obstacle collision avoidance, with an emphasis on user safety, and we aim to incorporate similar mechanisms in our design.

Another feature of the Olpin Group's toolbox is the "one drawer at a time" mechanism. This design allows only one drawer to be opened at a time, effectively preventing the toolbox from tipping over due to imbalance. This design element enhances user safety and efficiency, and we plan to integrate a similar feature in our toolbox.

Each of these projects serve as significant inspiration for our project. When combined in the Wrench Monkey Toolbox, they exemplify the blend of functionality, safety, and user-friendly design that we aspire to achieve with our project. By studying and learning from such past products, we aim to create a toolbox that not only meets but exceeds the standards set by these products, ultimately contributing to a safer and more efficient workspace.

Section 2.3: Goals and Objectives

The overarching goal of this project is to provide a product that increases shared workspace productivity and tool management. To tackle this central goal, a product was designed and constructed that has the ability to indicate tool locations and transport desired tools.

For the goal of tool transportation, we designed and constructed a chassis on top of which a toolbox was placed. More specifically, a drive system that consists of a motor driver circuit, an IR sensor array, and motors was selected that allows Wrench Monkey to traverse a work environment autonomously. For example, if there are inclines in the workspace, Wrench Monkey should not need to be pushed to get over the incline. Since some work spaces can be in environments with gravel and other rough terrain, either treaded tires or tracked tread are going to be used.

To achieve autonomy, sensors are used to guide Wrench Monkey to the desired workstation by tracing the path to each of the workstations using RFID tags to identify whether or not Wrench Monkey is at the desired location. Multiple IR sensors are used simultaneously in order to detect when Wrench Monkey is going off the path traced by the tape. To get to the various workbenches, the Wrench Monkey is placed in a closed loop with RFIDs placed at the Workstation locations. Because there are other obstacles in a workshop, ultrasonic distance sensors were also attached to the chassis to detect objects that could potentially obstruct the path of Wrench Monkey. For autonomy, a stretch objective would be to include voice recognition to call Wrench Monkey and/or to request specific tools. To accomplish this, would most likely require the use of artificial intelligence and signal processing, thus making this objective a stretch objective.

To fulfill the tool organization goal various objectives have been set to allow for new users to quickly find available tools for their tasks. For our first objective we implemented a pressure sensing system that is able to detect whether a tool has been placed in one of the locations in Wrench Monkey. Wrench Monkey has a Wi-Fi module so that the tool detection system can interface with a web application to keep track of the tools that are available. Similarly, if a tool is needed, but is being used, Wrench Monkey keeps track of who is using it by requiring a user login for the web application. In addition, the web application has the ability to request tools based on the task that is being completed by a user; for example, if some task A requires a hammer and a 10mm socket, the user is able to select the task A request which will prompt Wrench Monkey to highlight the required tools. Wrench Monkey is also equipped with a lighting system such that the requested tool(s) is/are highlighted to make tool identification faster. A stretch objective for the tool organization aspect of the project would be to determine whether a tool has been placed in the correct location. This would be done using RFID for unique tool identification

For long term use, Wrench Monkey should be powered by off-the-shelf battery hardware that can be swapped when overall capacity has been sufficiently decreased. Finally, in regard to the Wrench Monkey powering, a stretch objective would be creating a charging dock so that users do not have to plug Monkey Wrench into a power outlet.

Section 2.4: Features and Functionalities

There are multiple different features and functionalities that this project includes in order to reach the goals previously mentioned. The first functionality that the Wrench Monkey has, is the ability to be called to a workstation using line following. Using a web app, a user can request the Wrench Monkey to come to them from either its central starting location, or from another workstation. It will also be able to alert users if the tool that they have requested is already in use, and therefore unavailable.

The Wrench Monkey is also flexible and able to adapt to any work room through simply rearranging the path to be followed by the Wrench Monkey. As the toolbox is programmed to follow the path, changing the path in which it should take to a location or moving it from one room to another would not be difficult as all that needs to change is the location of the tape paths and the location of the station RFID cards. The toolbox is also equipped with ultrasonic distance sensors that allow it to detect if any objects are obstructing its path.

Another feature of the Tool Monkey is its ability to enhance tool organization. Using LEDs to highlight the requested tool helps the user find the correct tool more quickly and easily. This would be especially helpful in the case of needing a specific size of wrench, screwdriver, or other tool without having to go through multiple options first. This toolbox also has the ability to keep track of what tools are present and missing. This is done by using pressure sensors as well as requiring the users to log in to the website to request the tools. Additionally, the website has the ability to create custom tool combinations for recurring tasks. This would work through saving a list of tools needed for a specific task, and when a user wants to complete that task they could simply select the name of it on the website instead of having to select each individual tool that is required. This could help streamline the process as the website will keep track of what tools are needed for the project so the user may not need to remember specific sizes, and they also don't have to spend time selecting each item.

Section 2.5: Engineering Specifications

The following engineering specifications laid out were based on analysis of potential cost, feasibility, practicality, known size and weight, and intuition. Both software and hardware considerations were made when determining these desired parameters.

Motorized Carrier	
Carrier Weight (exc. battery)	< 7 kg.
Carrier Weight Capacity	< 15 kg.
Power Consumption	< 5W idle
Speed	< 250 mm/s
Battery Runtime	> 5 hours mixed use
Dimensions (LxWxH)	0.6m x 0.3m x 0.2m
Maximum Working Area	40 sq. m
Line Following Distance	> 5m

Toolbox	
Weight (exc. battery)	< 20 kg.
Dimensions (LxWxH)	0.6m x 0.3m x 0.9m
Tool Capacity	≥ 4 tools
Overall Project	
Dimensions (LxWxH)	0.6m x 0.3m x 1.1m
Total Weight	< 40 kg.
Communication Frequency	2400 MHz
Emergency Stop Latency	≤ 1.5s
Voltage Input	12V
Obstacle Detection Range	> 1m
Tool Detection Accuracy	> 90%
Cost	< $1000

Table 1 : Engineering Specifications

Section 2.6: Hardware Block Diagram

The block diagram below outlines each of the modules and specific pieces of hardware we expect to require with our current design plans.

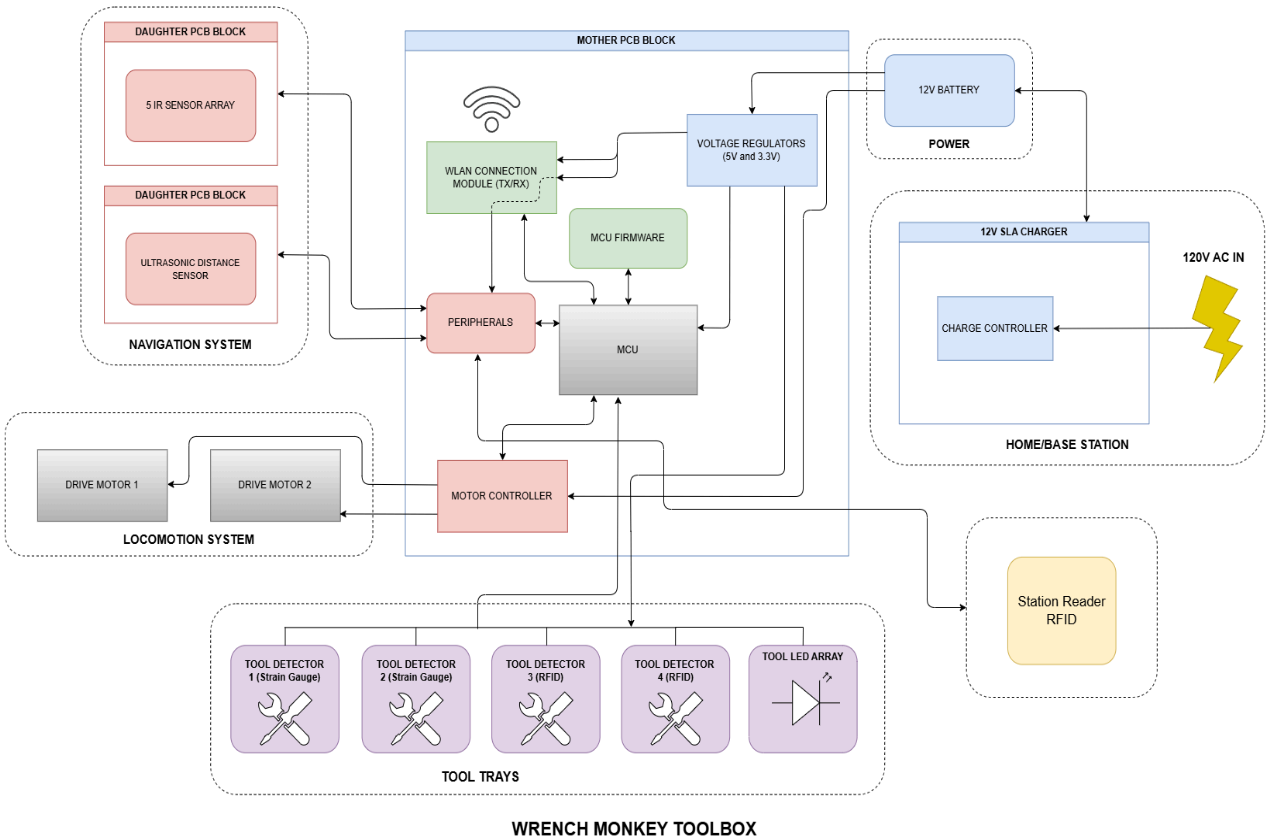

Figure 1: Hardware Block Diagram

Section 2.7: Software Flow Chart

The block diagram shown below shows the details of how the software portion of this project works. Note that further chapters will explain in more detail how each component works together.

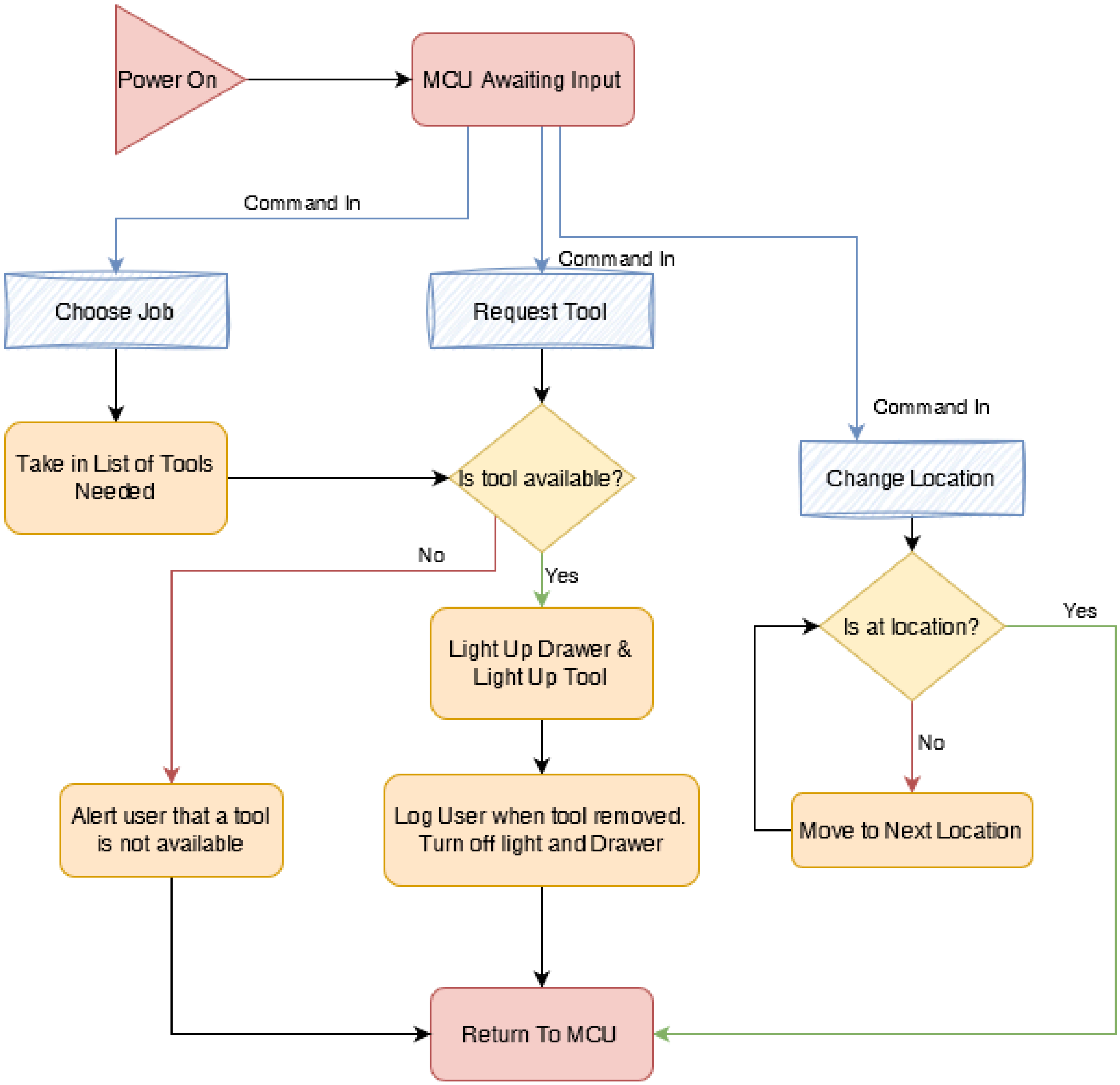

Figure 2: Software Block Diagram

Section 2.8: Prototype Illustration

The illustration below shows the plans for the Wrench Monkey smart toolbox.

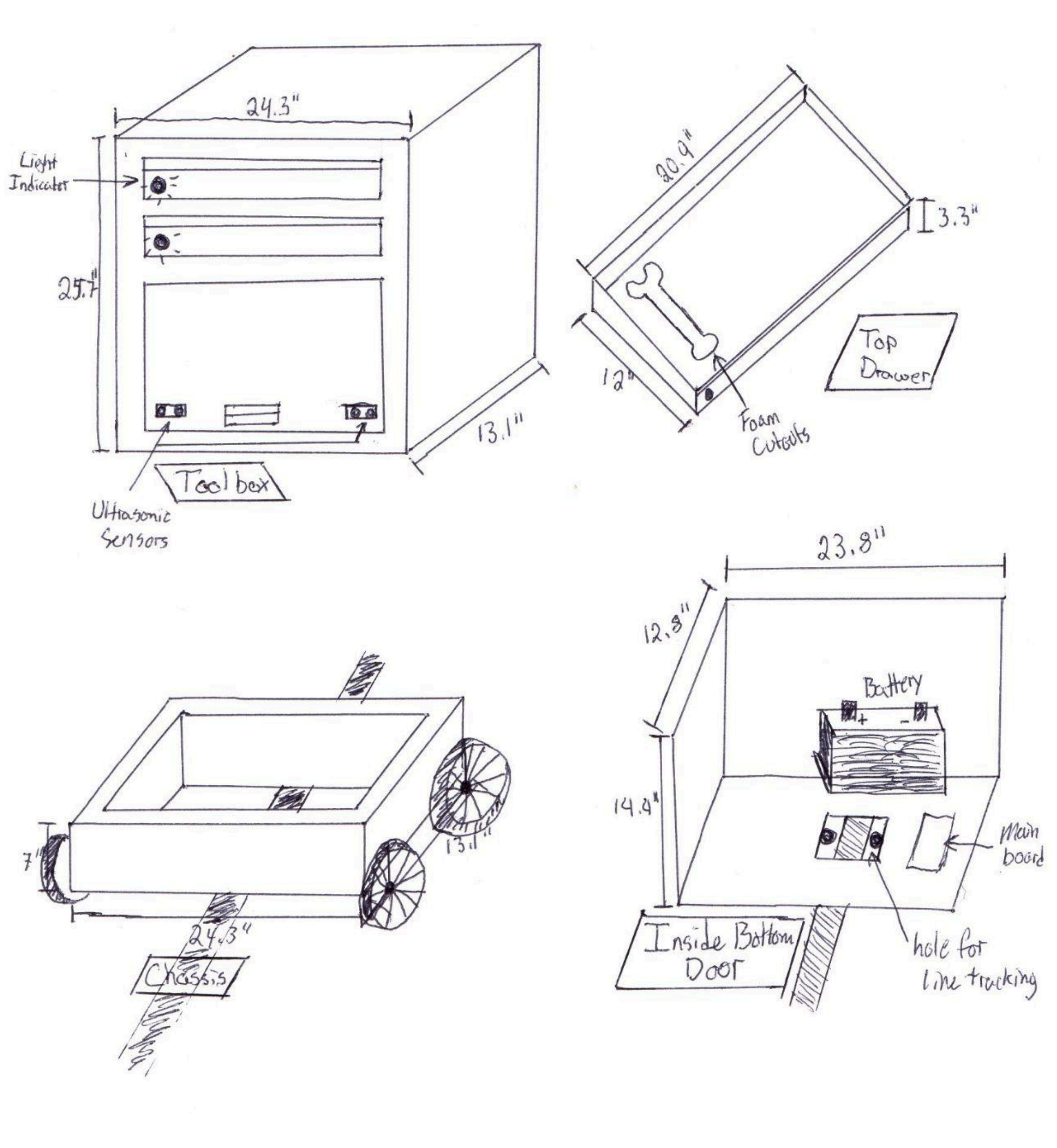

Figure 3: Several prototype sketches showing components and sizes

Section 2.9: House of Quality

The House of Quality, shown below, shows different engineering requirements, as well as different customer requirements, and the effects that they have on each other.

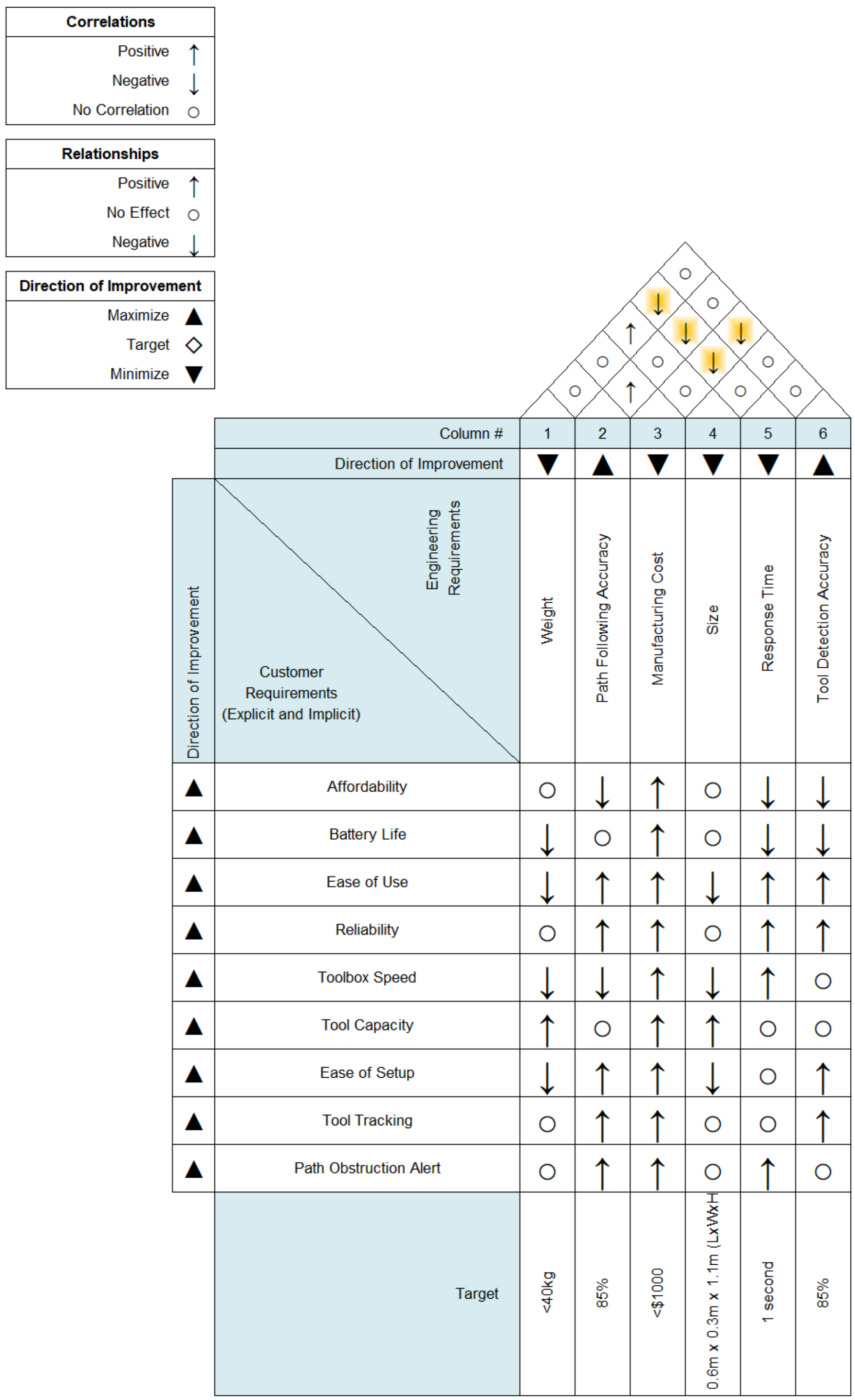

Figure 4: House of Quality

Chapter 3: Research and Part Selection

This chapter explains all of the research done in preparation for this project. It addresses all of the options considered for the different parts and methods that could be used to accomplish the desired features and functionalities of the Wrench Monkey toolbox. It then explains which option was ultimately chosen, and why it was decided that the selected option would be the best for the purposes of our project, taking into account factors such as ease of use, cost, and effectiveness.

Section 3.1: Control System Research

Due to the need for Wrench Monkey to travel to various workstations that could be oriented in a plethora of ways, black tape (or printed black line) along with RFID tags are used for guidance so that the path of Wrench Monkey can be easily rearranged. To follow the tape, PID control was selected to be used as our line following algorithm as opposed to other options. The different control techniques consist of bang-bang control, PID control, model predictive control (MPC), and reinforcement learning.

Section 3.1.1: Bang-bang Control

Bang-bang control represents one of the most straightforward techniques in robotic control systems. Its simplicity lies in its binary nature: it operates with only two control states—on or off. This means that when the system's conditions breach a predetermined threshold, the control signal is activated, initiating a response in the system. For instance, in the context of a line-following robot like Wrench Monkey, one motor could be instructed to accelerate while the other decelerates when the robot veers off course, thereby correcting its trajectory. This is accomplished via line detection with integrated color sensors.

This control scheme finds most applications in systems that implement rudimentary control responses, as is the case in simple line-following robots. Despite its simplicity, bang-bang control effectively serves as a functional control mechanism for robots, and is often employed in initial testing phases due to its ease of implementation. However, the caveat of its simplicity lies in the tendency to produce somewhat erratic movements, resulting in less smooth operation compared to more sophisticated control methods.

In the case of Wrench Monkey, while bang-bang control may ensure basic line following capability, its inconsistent movements lack the precision smoothness desired in optimal performance scenarios on a work floor. Therefore, while it served as an adequate starting point for experimentation and initial testing, the ultimate objective transitioned to more advanced control strategies. These more refined (and therefore, more complicated) techniques offer superior line-following precision and smoother movement, improving the overall system greatly.

Section 3.1.2: Proportional - Integral - Derivative Control

PID control, standing for Proportional, Integral, and Derivative control, represents a sophisticated approach to regulating systems, and is applicable to line following in robotics. Its effectiveness lies in its ability to dynamically adjust control signals based on three crucial factors: the current error, the accumulated error over time, and the rate of change of the error. The general equation describing PID control is shown below:

$$u(t) = K_p e(t) + K_i \int e(t) + K_d$$

Proportional control forms the core of the PID algorithm, exerting a control influence proportional to the current error. This means that larger errors result in more significant control adjustments, thereby enabling rapid response to deviations from the desired state, such as veering off course of a line. The integral control aspect complements this by addressing persistent errors that may not be corrected solely by proportional control. By accumulating the error over time, integral control ensures that steady-state errors are mitigated, which leads to improved overall accuracy and stability.

Additionally, the derivative component of PID control serves to dampen rapid changes in the error, thereby reducing overshoot and enhancing system stability. By adjusting the control output proportionally to the rate of change of the error, the derivative term effectively moderates the system's response, preventing it from oscillating or overshooting the desired setpoint. In the case of Wrench Monkey, this prevents the erratic movement that would otherwise be seen with Bang-Bang control schemes.

Although PID controllers inherently have a higher level of complexity compared to simpler control schemes like bang-bang control, their versatility and effectiveness make them practical and desirable in numerous applications. By carefully tuning the proportional, integral, and derivative parameters, PID controllers can be optimized to meet specific design criteria, such as minimizing overshoot, reducing settling time, and improving overall system responsiveness. This adaptability and precision render PID control highly suitable for tasks requiring precise control, dynamic response, and robust performance.

Section 3.1.3: Model Predictive Control

Model Predictive Control (MPC) is a useful control system methodology capable of optimizing and achieving project objectives while respecting system constraints. Unlike traditional control methods, such as the earlier discussed PID control or Bang-Bang control, MPC employs a predictive approach, which utilizes pre-programmed mathematical models to forecast system behavior and select optimal control signals accordingly based on what has already been navigated. This predictive capability distinguishes MPC from PID control, as it considers future system states based on current information, enabling more strategic decision-making over a greater distance of travel.

An example application of MPC can be seen in autonomous robotic systems, where it utilizes mathematical models of the system to optimize parameters like power consumption or travel time, all while ensuring adherence to operational constraints. This ability to anticipate future outcomes allows MPC control schemes to make decisions that balance the desired movement behavior effectively.

Continuing this, MPC is composed of multiple control techniques, each of which can be tailored to conform to specific system dynamics (like line following), yet follows a common predictive framework based on the modeling of the system. This versatility allows MPC to address multiple control challenges, including multivariable systems (such as navigation on inconsistent terrain), without substantially increasing the required computational complexity.

However, the implementation of MPC has inherent limitations. Notably among these is the reliance on accurate mathematical models of the system, which requires accurate modeling efforts to ensure reliable predictions. Additionally, the predictive nature of MPC based on math has a higher computational cost compared to simpler control methods, as it involves predicting future behavior and optimizing the control actions based on these predictions. As a result of this, since MPC offers unparalleled predictive capabilities and versatility, its effectiveness hinges on the quality of the system model and computational resources available for implementation.

Section 3.1.4: Reinforcement Learning (RL)

This approach to control a plant is interesting in that the controller must “learn” the desired control law, also called the policy, to achieve the desired system behavior. Additionally, there are two categories of RL approaches that can be used: model-free and model-based RL. In model-free RL, the policy is learned solely by interacting with the environment. On the other hand, model-based RL has a predetermined model for the system that is used to predict the state transitions and the rewards of the system to determine the optimal actions to be taken. In previously made line following robots, RL value iteration algorithms have been used to learn the desired policy.

Although RL is a solution that would have most likely led to an optimal solution, it would have required more computational efforts to update model parameter values for the deep neural network that would approximate the optimal line following policy. In addition to the computational cost of implementing deep RL, the members of our team are not experienced in deep reinforcement learning algorithms which could lead to various problems in the process that would not have been worth the time spent fixing them.

Section 3.1.5: Control System Comparison and Selection

In the paper by Saadatmand, et al., it was shown that the p-controller performed similarly to the RL methods. That being said, PID control or MPC has been implemented for Wrench Monkey because reinforcement learning will require time to train and will increase the chance for coding mistakes to be introduced without providing a significant improvement to the performance. Additionally, RL is not as easily tuned to have specific behavior because instead of directly controlling parameters, the agent's reward system would have to be adjusted until the agent shows the desired behavior.

Although bang-bang control is the easiest of the controller schemes described, it was only used for initial testing, later replaced with the more sophisticated control technique, PID, since it allows for smoother behavior when tuned properly.

PID control was implemented because it did not require a mathematical model. This is an advantage over MPC due to the need to model the plant behavior accurately so the controller is able to make predictions and optimize controller outputs that fulfill any constraints that are set.

Control Technique	**Mathematical Modeling Required**	**Tuning Method**
Bang-Bang	No	-Trial and error
PID	No	-Trial and error -Ziegler Nichols
MPC	Yes	-Changing objective function
RL	No	-Change rewards -Change reward structure

Table 2: Control System Comparison

Section 3.2: Mobile Application & Desktop Website

Unlike traditional robots that rely on a physical user interface for interactions, Wrench Monkey adopts a modern approach by using a mobile application and a desktop website for control and management. This allows users to remotely command the robot's movements, access tool inventory, request specific tools, and receive real-time updates on tasks and progress. This type of setup usually requires a full stack application to function correctly.

A full stack application refers to a software development approach where both the front end and back end, or client side and server side, components are developed together to create an integrated system. The front end consists of user interface elements such as web pages, mobile app screens, and graphical elements. Meanwhile, the back end side consists of the server, database, and application logic that manages data and processes requests.

Section 3.2.1: LAMP Stack

The LAMP Stack, an acronym for Linux, Apache, MySQL, and PHP, represents a popular beginner full stack development approach that is perfect for building dynamic and interactive websites and applications. LAMP stack was one of the first open source software stacks for the web and is still a common way to deliver web applications as sites like WordPress and Drupal still run on it.

Firstly, the foundation of the LAMP stack is the operating system Linux. As a free and open source operating system that has been around for more than two decades, Linux provides a solid foundation for hosting web applications. Its widespread adoption in web servers means there is an abundance of documentation available, allowing developers to customize their server setups according to their specific requirements. Renowned for its stability and security features, Linux stands as a very popular choice for server deployments in the LAMP stack ecosystem. A key advantage is its compatibility with diverse hardware and software configurations, offering flexibility and scalability to meet varying project needs.

Secondly, Apache is the web server software that handles HTTP requests and delivers the web assets making it accessible to anyone in the public domain. To illustrate this, consider a scenario when a user inputs a URL to access a website's home page. Apache then processes this request, locating the corresponding HTML page, typically named index.html, and then sends it back to the user's web browser for viewing. This seamless handling of requests and delivery of web pages shows Apache's primary role in facilitating user access with web applications within the LAMP stack. The Apache web server is further emphasized by its open source nature, which makes it very customizable giving it a very feature experience.

Next, MySQL serves as the relational database management system providing a robust platform for storing and managing application data. Most of the time, this database management system is communicated with over command line giving it an older style, but there have been efforts to create user friendly graphic interfaces such as phpMyAdmin making it more intuitive for developers. Regardless, it is able to organize structured data efficiently by using the SQL or Structured Query Language capabilities to perform complex queries. One of the key strengths of MySQL is in its ability to handle large volumes of data giving it an ability to run complex websites and distribute data across multiple servers, accommodating future growth.

Lastly, PHP serves as the dynamic scripting language in the LAMP stack. This language works seamlessly with Apache to facilitate the creation of dynamic web pages. Since you cannot use HTML alone to perform dynamic processes like pulling data out of a database, PHP provides the necessary functionality by allowing developers to embed PHP code directly into HTML pages. This type of language is designed for efficiency, by extending existing web development paradigms such as object oriented programming, procedural programming, and functional programming. It allows for server-side processing once integrated in apache giving thousands of uses in website development such as handling form submissions, interacting with databases, and building interactive and data-driven web experiences.

To recap, Linux provides a stable and secure operating system for hosting web applications. Apache serves as the web server software handling HTTP requests. MySQL is the relational database management system that organizes and manages structured application data with SQL queries. Finally, PHP is the dynamic scripting language that facilitates the creation of interactive web pages.

Section 3.2.2: MERN Stack

The MERN stack, an acronym for MongoDB, Express, React, and Node, represents another popular choice for full stack application development. In today's time, MERN stacks are used extensively by developers and companies worldwide, especially in e-commerce, social media, and data analytics. This allows developers a versatile and efficient platform for building modern web applications with an enhanced streamlined development process. In my experience, MERN stacks make it incredibly easy to produce IOS and Android applications based on the web experience due to the Express and React framework which will be discussed in detail further later.

Firstly, MongoDB acts as the document database within the MERN stack. MongoDB is a very well known NoSQL database so it works opposite of the LAMP stack. Instead of using tables to separate data within the database like MySQL does, MongoDB uses collections which are groups of BSON, or Binary JavaScript Object Notation, files. Moreover, this allows Mongo to store large amounts of data, handling terabytes of data efficiently. Unlike traditional databases, MongoDB provides a powerful query language allowing for the retrieval and manipulation of data swiftly.

Second, Express makes up the server-side web framework in the MERN stack. It wraps HTTP requests and responses, making it easy to handle routing and mapping URLs to server-side functions. As a minimalist and flexible Node.js web application framework, Express provides a robust set of features for developing both web and mobile applications. One of its key strengths is the range of built in middleware that enables developers to enhance the request-response cycle, making it possible to streamline the development of APIs. Developers can define routes using HTTP methods such as GET, POST, PUT, and DELETE, handling the routing logic efficiently.

Next, React represents the top tier of the MERN stack, providing a framework for building dynamic client-side applications in HTML. React is a front end JavaScript library developed by a software engineer at Meta, which enables developers to create interactive user interfaces efficiently. It is known for its component based architecture allowing developers to create reusable UI components improving code organization and maintainability. One of the key features of React is its virtual DOM, or Document Object Model, implementation which optimizes rendering by only updating necessary parts of the UI. This leads to faster rendering speeds, especially in applications with dynamic content.

Lastly, the Node is its own framework that runs Express within it, forming the backend foundation of the MERN stack. Node.js is a runtime environment that allows developers to run JavaScript code on the server-side. When combining Node and Express, developers can easily make scalable and efficient server-side applications that handle HTTP requests. Node.js also has a vibrant ecosystem with a wide range of npm, or Node Package Manager, modules and libraries which allows for seamless addition of functionality and new tools.

Section 3.2.3: Stack Comparison and Selection

When developing the user interface portion of the Wrench Monkey project, picking the correct full stack development is crucial. The choice between LAMP and MERN stacks significantly impacts the performance and functionality of the application.

The LAMP stack, composed of Linux, Apache, MySQL, and PHP, has been a go-to solution for web development for many years. It offers a stable and robust environment, with Linux providing a secure operating system foundation, Apache serving as a reliable web server, MySQL handling data management efficiently, and PHP enabling dynamic content generation.

On the other hand, the MERN stack, composed of MongoDB, Express, React, and Node.js, represents a modern and dynamic approach to full stack development. MongoDB’s NoSQL database structure allows for flexible data handling, Express streamlines the server-side development, React facilitates interactive and responsive user interfaces, and Node.js enables efficient server side processing.

For the Wrench Monkey project, considering the emphasis on real-time updates, remote control functionalities, and a dynamic user interface, the MERN stack offers many advantages over the LAMP stack. React’s component-based architecture aligns well with the need for reusable and interactive UI components, while Express allows for the easy transferability of content between web and mobile applications streamlining the development process.

Stack	Development Experience	Scalability	Performance	User Interface Flexibility
LAMP	Established, Abundant Docs	Scalable for medium sized apps	Good Performance	Limited UI libraries, Python for dynamic content
MERN	Modern, Growing Community	Scalable for large apps	High Performance	Rich UI libraries, React for dynamic content
Stack	Front End	Web Server	Database	Back End
LAMP	JavaScript	Linux/ Apache	MySQL	PHP/PERL/Python
MERN	React (JavaScript)	Node	MongoDB	Express

Table 3: Stack Comparison

Section 3.3: Motors

The Wrench Monkey is equipped with front wheel drive. The following section describes how the best motors were chosen for this project. The options considered are brushed DC motors, brushless DC motors, stepper motors, and servo motors.

Section 3.3.1: Brushed DC Motors

Brushed DC motors offer several advantages for robotic propulsion on the ground, primarily due to their simplicity of operation. These motors can be easily driven using a simple analog DC voltage from a battery, or any other power source with sufficient current capability, requiring minimal additional circuitry for basic functionality. This simplicity makes brushed DC motors particularly attractive for applications where ease of integration and operation are prioritized, allowing for simple integration and reduced complexity in system design.

Furthermore, brushed DC motors are known for their robustness and durability, thanks to their simple construction and straightforward design. As a result, brushed DC motors can withstand harsh operating conditions, ensuring consistent performance over extended periods. This reliability is important in ground-based robotic systems where uptime and continuous operation is essential.

However, brushed DC motors also have several limitations that must be considered. One notable drawback is their limited efficiency and lifespan compared to other motor types, such as brushless DC motors. The presence of brushes within the motor introduces friction and wear, leading to eventual degradation of performance and reliability over time. This limitation therefore requires regular maintenance and replacement of brushes to ensure continued operation, adding to the overall operational cost and complexity of the system.

Additionally, without an additional reduction gearbox, the output RPM of brushed DC motors is too high (on the order of hundreds or thousands) for certain applications, including the Wrench Monkey. This high RPM output can limit the motor's suitability for tasks requiring precise control or heavy load handling, necessitating additional mechanisms such as gearboxes to achieve the desired output RPM/torque. The inclusion of such a gearbox introduces additional drawbacks. A motor with sufficient torque and no gearbox would be too large, heavy, and power-hungry for the Wrench Monkey, compromising its mobility and efficiency. Moreover, brushed DC motors generally exhibit limited torque output with direct drive applications, especially in smaller sizes, further constraining their utility for applications demanding high torque requirements. In summary, while brushed DC motors offer simplicity of operation, reliability, and durability, they also come with limitations such as limited efficiency, lifespan, and torque output. Careful consideration of these factors is essential when selecting brushed DC motors for ground-based robotic propulsion, ensuring compatibility with project requirements and operational constraints.

Section 3.3.2: Brushless DC Motors

Brushless DC (BLDC) motors offer several advantages and disadvantages when used for robotic movement purposes. On the positive side, BLDC motors are known for their high efficiency, which translates to longer operating times and reduced energy consumption compared to brushed DC motors. Additionally, BLDC motors have a longer lifespan due to the absence of brushes, which reduces friction and wear within the motor. This durability is particularly advantageous in robotic applications where longevity and reliability over extended periods is crucial, such as industrial use.

Moreover, BLDC motors are capable of delivering higher power and torque, making them well-suited for applications requiring greater propulsion force, such as moving heavy loads in the Wrench Monkey project. These performance characteristics enhance the overall capabilities and versatility of ground-traversing robotic systems, enabling them to navigate in industrial environments effectively.

However, utilizing BLDC motors for movement also comes with some drawbacks. One notable drawback is the requirement for specialized electronic speed controllers (ESCs) to control the motor's speed and direction entirely. These ESCs add complexity to the overall system design, require additional circuitry, and add an additional point of failure, which increases the overall cost and complexity of the robotic system.

Furthermore, BLDC motors may introduce electromagnetic interference (EMI) issues due to the rapid switching of currents within the motor windings. This interference can affect nearby electronic components and sensors, especially since wireless RF communication is in use for the project, which can potentially impact the overall performance and reliability of the system. Shielding or filtering measures may be necessary to mitigate these effects, which will add further complexity to the system design.

Despite these challenges, the advantages of BLDC motors, such as their high efficiency, durability, and power output, generally make them a preferred choice for many ground-based robotic propulsion applications. With proper design and implementation, BLDC motors can significantly enhance the performance and capabilities of robotic systems such as the Wrench Monkey, enabling them to tackle a wide range of tasks efficiently and reliably.

Section 3.3.3: Stepper Motors

Stepper motors present both advantages and limitations when utilized for robotic movement systems. One notable advantage of stepper motors is their suitability for applications requiring high precision movement. Unlike other types of motors, stepper motors move in discrete steps, allowing for precise control over position and velocity. This characteristic makes them well-suited for tasks that demand accurate positioning, such as robotic arms or CNC machines.

Additionally, stepper motors typically exhibit high torque output, especially at low speeds. This high torque capability enables stepper motors to effectively drive mechanisms with significant resistance or inertia, making them suitable for applications involving heavy loads or demanding terrain. The ability to generate high torque at low speeds enhances the stability and reliability of ground-based robotic systems, which ensures consistent performance in different environments.

However, stepper motors also have important limitations that need to be considered when designing the system. One such limitation is their relatively lower maximum RPM compared to other types of motors, such as brushed or brushless DC motors. This lower RPM can restrict the speed at which a robotic system can operate, potentially impacting its overall efficiency and responsiveness, especially in applications requiring rapid movement or higher-speed traversal like expected with Wrench Monkey.

Moreover, stepper motors require precise control electronics to operate. Unlike some other types of motors, such as brushed DC motors, which can be controlled using purely DC voltage, stepper motors rely on specialized drivers to precisely control step sequences and motor movement. This requirement for dedicated control electronics adds complexity to the system design and generally increases overall cost and complexity, reducing reliability of the system.

Despite these limitations, the precision, high torque output, and suitability for applications requiring precise movement make stepper motors a strong choice for ground-based robotic propulsion applications such as Wrench Monkey. With proper design and implementation, stepper motors can effectively perform the required tasks with high accuracy and efficiency.

Section 3.3.4: Servo Motors

Servo motors offer distinct advantages when used for robotic movement and control on the ground. One significant advantage of servo motors is their precision movement control, which is facilitated by closed-loop feedback systems via integrated rotary encoders, which in turn provide accurate positional information. This feedback mechanism enables servo motors to achieve precise movement and maintain desired positioning and velocity of whatever is attached, making them well-suited for applications requiring high levels of accuracy, such as robotic manipulation and positioning systems.

Additionally, servo motors often exhibit high torque output relative to their compact size, due to reduction gearboxes attached to the physical motor itself This combination of compactness and torque makes servo motors suitable for applications where space is limited, and a substantial force is required, such as in small-scale robotic platforms like the Wrench Monkey, where heavy loads must be transported. The ability to deliver significant torque in a compact form factor enhances the versatility of ground-based robotic systems that employ their use in the design.

Another advantage of servo motors is their simplicity of operation, as they do not require additional drive circuitry for basic functionality. Unlike some other types of motors, such as stepper motors or brushless DC motors, which rely on specialized control electronics, servo motors can be operated using a simple analog DC voltage. This straightforward operation makes integration into a system simple and reduces the complexity of the overall system design, making servo motors an attractive choice for applications where simplicity and ease of use are important. The ability to operate with minimal additional circuitry enhances the versatility of servo motors, allowing them to be easily incorporated into a wide range of robotic systems, including the Wrench Monkey, with minimal hassle or complexity.

However, servo motors also present certain limitations that need to be considered when designing a robotic system. Like stepper motors, a major limitation is their lower maximum RPM compared to other types of motors, such as brushed or brushless DC motors. This limitation can impact the speed at which a robotic system can move, potentially affecting its overall performance and responsiveness.

Moreover, there exists a trade-off between the RPM and torque capabilities of servo motors. While servo motors are capable of delivering high torque, increasing the RPM necessary for faster movement decreases torque output for the same size, due to gearbox reduction ratios being changed. This trade-off requires careful consideration to strike a balance between speed and torque of Wrench Monkey, ensuring that the system can move quickly enough and can effectively handle heavy loads as required by the engineering specifications.

With this, servo motors offer precise positional control, high torque output, and compact size, making them well-suited for various ground-based robotic propulsion applications. However, their limitations in terms of maximum RPM and the need to balance speed with torque must be carefully managed to ensure optimal performance and efficiency in robotic systems like the Wrench Monkey.

Section 3.3.5: Motor Comparison and Selection

In the development of the Wrench Monkey project, the selection of servo motors was the clear choice due to their superior performance across several key criteria. Most importantly among these factors is the servo motor's exceptionally high torque capacity, which is a critical attribute for effectively moving heavy loads – a primary requirement for the Wrench Monkey's design. With its gearbox-dependent torque output, the servo motor provides the necessary power to maneuver substantial weights with ease and precision, ensuring the Wrench Monkey can operate correctly.

Precision movement is another important requirement in the functionality of the Wrench Monkey, particularly in the navigation aspect. Here, servo motors stand out through their integration of rotary encoder feedback systems, enabling precise control over rotational movements. This feature is a necessity in facilitating accurate navigation and manipulation, ensuring that the Wrench Monkey operates with precision in its intended environment.

Ease of control was also an important aspect, as it significantly influences the practicality and usability of any motor technology. Servo motors excel in this regard by requiring only analog voltage inputs for power, simplifying the control process significantly compared to BLDC or stepper motors. This ease of control streamlines integration efforts and minimizes complexities when designing the system.

Furthermore, the compact size and lightweight nature of servo motors align with the Wrench Monkey's design objectives, where space optimization and portability are a primary concern. Unlike the other discussed motor technologies, servo motors offer a favorable balance of performance in terms of RPM/torque output, and form factor, enabling the construction of a compact chassis without compromising on power or functionality. This ensures that the Wrench Monkey remains agile and adaptable across diverse operating conditions, maximizing its utility and practicality, especially in varying industrial environments.

In contrast, the alternate motor technologies were found lacking in one or more critical areas essential for the successful realization of the Wrench Monkey project. Whether it be insufficient torque output or RPM, limited precision, cumbersome control mechanisms, or excessive size and weight, these shortcomings showed the suitability of servo motors for meeting the requirements of the Wrench Monkey's design specifications. Through their combination of high torque, precision, ease of control, and compact form factor, servo motors emerge as the optimal choice. The table below compares the qualitative characteristics of each motor type considered.

Motor Type	RPM	Torque	Precision
Brushed DC	3000-12000	0.00102 - 0.01020 kg*cm	10+°
BLDC	2000-6000	0.00102 - 0.00510 kg·cm	10+°
Stepper	200-600	4.5 - 5 kg*cm	0.9°
Servo	13-1600	3 - 70 kg*cm	5.62°

Table 4: Motor Properties Comparison

Section 3.4: Tool Detection Sensors

A major functionality of the Wrench Monkey is the ability to determine if a tool is present or not within the toolbox drawer. To do this, multiple different sensors were considered to determine which would be the best option for this project. The following section explains the options, as well as the selection which is implemented into the final product.

Section 3.4.1: Resistive Strain Gauge

Utilizing resistive strain gauges for detecting tool presence in a slot within a toolbox offers several advantages. Firstly, these strain gauges are relatively simple to integrate into the toolbox design, requiring minimal additional components since it is a purely resistive measurement solution. Their straightforward implementation streamlines the manufacturing process and reduces overall costs, making them a cost-effective solution for tool detection applications like in the Wrench Monkey.

Additionally, resistive strain gauges are desirable because of their low cost, making them accessible for a wide range of applications, notably tool detection in toolboxes. This affordability enhances their suitability for applications where economics and overall pricing are concerned.

Moreover, resistive strain gauges offer flexibility in terms of available shapes and rigidity of the gauge itself, which can accommodate different toolbox designs and configurations. Whether integrated into flexible slots or rigid compartments, the strain gauges can be purchased to fit specific dimensions and requirements given their widespread availability.

Additionally, resistive strain gauges provide reliable and repeatable detection of tool presence within the toolbox, ensuring proper inventory management can work with the toolbox software. Their sensitivity to strain variations enables detection of even small tool movements or displacements.

However, despite their advantages, resistive strain gauges have limitations that need to be considered. For instance, their sensitivity to external factors such as temperature, humidity, or repeated mechanical stress can affect their accuracy and reliability over time. As such, proper calibration and maintenance may be required to ensure consistent performance and functionality in the long term.

With this, resistive strain gauges offer a simple, cost-effective, and flexible solution for detecting tool presence in a slot within a toolbox. Their ease of integration, low cost, flexibility, and reliable performance make them a practical choice for enhancing organization and efficiency in toolbox management applications.

Section 3.4.2: Capacitive Load Cell Detection

Using capacitive weight detection sensors for tool presence detection is another potential option in the project. One notable advantage is the sensitivity of capacitive sensors to weight variations, regardless of material type, enabling detection of tools within the toolbox. This high level of sensitivity allows for accurate inventory management, ensuring that missing tools are quickly identified and located.

Additionally, capacitive weight detection sensors offer a non-contact method of detection, which minimizes wear and tear on both the tools and the sensors, prolonging their lifespan and reducing maintenance requirements. Moreover, the absence of physical contact eliminates the risk of damage or deformation to delicate tools or the sensor itself, protecting the parts and extending longevity and functionality over time.

Furthermore, capacitive weight detection sensors can be easily integrated into the toolbox design, offering flexibility in terms of placement and configuration. Whether mounted directly beneath the toolbox compartments or embedded within the toolbox structure, these sensors can be customized to fit various dimensions and layouts, making them desirable for their versatility while designing the toolbox.

However, despite their advantages, capacitive weight detection sensors have limitations that need to be considered. One potential drawback is their susceptibility to environmental factors such as temperature and humidity variations, which have a direct impact on capacitance, along with electromagnetic interference, which may affect their accuracy and reliability. Additionally, calibration may be required to ensure consistent performance and minimize false detections, adding complexity to the integration and continued use of the sensor.

Alongside this, capacitive sensors generally have limitations in terms of the maximum weight they can detect, and the accuracy as weight measurement scales change. Importantly, the cost of capacitive weight detection sensors is higher compared to other detection methods, potentially impacting the overall cost-effectiveness of the toolbox system. Careful evaluation of these factors is essential when selecting the weight detection sensor to be used for Wrench Monkey.

Section 3.4.3: Photoelectric Detection

Implementing photoelectric-based tool detection systems, such as IR-based proximity sensors, for detecting tools in a toolbox offers various advantages and considerations. One significant advantage is the non-contact nature of photoelectric sensors, which, like capacitive, eliminates the need for physical contact with the tools. This approach reduces the risk of damage or wear to both the tools and the sensors, ensuring their longevity and minimizing maintenance requirements.

Furthermore, photoelectric sensors provide reliable and consistent detection of tools within the toolbox, regardless of factors such as tool material, size, or orientation. This versatility makes them suitable for a wide range of tool types and configurations, enhancing the flexibility and adaptability of the toolbox detection system.

Alongside this, photoelectric sensors offer fast response times and high accuracy, enabling rapid detection of tool presence within the toolbox. This ensures efficient organization and inventory management, allowing the system to quickly detect tools as needed.

Additionally, photoelectric sensors can be easily integrated into the toolbox design, offering flexibility in terms of placement and configuration. Examples of photoelectric sensors that can be used for tool detection include infrared (IR) proximity sensors which emit infrared light and detect the reflection or absence of this light to determine the presence or absence of a tool within the detection zone. Another example is a laser distance sensor. These sensors use laser beams to measure the distance to an object, enabling precise detection of tool presence within the toolbox. Lastly there are optical sensors, which use visible light to detect the presence or absence of tools, providing reliable detection.

These sensors usually come equipped with an independent light source to operate in various lighting conditions.

However, despite their advantages, photoelectric-based tool detection systems have limitations that need to be considered. For example, these sensors are susceptible to environmental factors such as ambient lighting conditions or debris such as dirt and dust (common in industrial workplaces), which can affect their accuracy and reliability. Additionally, calibration may be required to optimize sensor performance and minimize false detections, adding complexity to the setup and maintenance process.

Furthermore, the cost of photoelectric sensors may vary depending on factors such as sensor type, brand, and features, which may impact the overall cost-effectiveness of the toolbox detection system. Careful evaluation of these factors is essential when determining which sensor to use.

Section 3.4.4: RFID Detection

Implementing a RFID tag-based detection system, where RFID stickers are placed on tools, offers several advantages. One significant advantage is the cost-effectiveness of RFID tags, which are relatively cheap and readily available in various sizes and configurations, and are compatible with different materials, such as metal which is commonly used for tool construction. This affordability makes RFID tag-based detection systems a practical solution for tool management applications, allowing for widespread adoption and deployment.

Importantly, RFID tag-based detection systems offer the capability to not only detect the presence of a tool but also identify specific tools based on their unique RFID tags. This enables accurate inventory tracking and management, ensuring that each tool is accounted for and located within the toolbox. Additionally, RFID tags can store additional information such as tool specifications or maintenance history, enhancing the overall toolbox management system.

Furthermore, RFID tag-based detection systems provide a non-contact method of tool detection, eliminating the need for physical contact with the tools. This approach reduces the risk of damage or wear to both the tools and the detection system, ensuring their longevity and minimizing maintenance requirements.

However, despite these advantages, RFID tag-based detection systems may have important limitations and drawbacks to consider. Notably, the requirement for individual RFID readers for each tool slot or compartment within the toolbox. This drives up complexity and cost, particularly in applications where a large number of tools are used, as each RFID reader must be integrated and managed separately.

Moreover, RFID tag-based detection systems may be susceptible to interference from metallic objects or other sources of electromagnetic interference, which can affect their accuracy and reliability. Additionally, the range of RFID readers is limited, requiring careful placement of either the sensor or the tool to ensure reliable detection of tools within the toolbox. All of these factors must be balanced to determine if RFID is suitable for the Wrench Monkey system.

Section 3.4.5: Tool Detection Sensor Comparison and Selection

In the design considerations for tool detection within the Wrench Monkey toolbox, resistive strain gauges were decided as the optimal choice, primarily due to their low cost and ease of implementation. Unlike the alternate sensing technologies discussed, namely capacitive and photoelectric sensors, resistive strain gauges offer a straightforward solution that only requires the measurement of resistance change, a capability readily supported by most microcontroller chips. This simplicity in how the sensor works significantly simplifies the integration process, eliminating the need for complex additional circuitry and reducing overall implementation costs.

Furthermore, the fundamental principle of how resistive strain gauges work means they are available in various form factors on the market. This widespread availability of different shapes and sizes significantly simplifies the selection process, allowing for the identification of a suitable strain gauge configuration that can be used within the Wrench Monkey toolbox. By placing the sensors in the tool slots beneath the tool, the strain gauges are then capable of detecting tool presence within the toolbox, as the gauge is expanded when the tool is present, changing its measured resistance value.

Although resistive strain gauges inherently have lower accuracy compared to the other sensing technologies such as photoelectric or capacitive sensors, the binary nature of our project is adequately met by the strain gauge. The ability to detect the presence or absence of a tool suffices for the intended purpose.

However, recognizing the potential limitations of resistive strain gauges in distinguishing between similar tools, a small-scale implementation of RFID tool detection will complement the primary sensing mechanism for a select few tools. This addition allows the toolbox to not only detect the presence of a tool but also verify its type within a tool slot, mitigating the risk of accidental tool switching. By combining the simplicity and affordability of resistive strain gauges with the precision of RFID technology, the Wrench Monkey toolbox achieves a comprehensive and efficient tool detection system tailored to its engineering specifications. The table below outlines the main qualitative factors used to compare each sensing technology.

Sensor Type	Cost	Size	Accuracy	IO Pins Required
Strain Gauge	< $5	0.75 x 7 in.	95%	1
Capacitive	$10+	1 x 1 in.	90%	1
Photoelectric	$5-10	0.5 x 1 in.	95%	2
RFID	$5	1.5 x 2.3 in.	99%	5

Table 5: Tool Detection Sensors Comparison

Section 3.5: Batteries

The following section describes the different battery options that were considered to power the Wrench Monkey.

Section 3.5.1: Lithium Ion Battery

Utilizing lithium-ion batteries for the project has many distinct advantages over other battery technologies. One significant advantage of lithium-ion batteries is their high energy density, allowing for compact and lightweight designs while providing sufficient energy storage for the device's use. This high energy density makes lithium-ion batteries well-suited for applications where space and weight constraints are important considerations, as is the case with Wrench Monkey.

Importantly, lithium-ion batteries are available in various chemistries, like lithium iron phosphate (LiFePO4) batteries, which offer advantages such as improved safety and longer lifespan compared to other lithium-ion battery chemistries. This versatility means that different chemistries can be chosen depending on the use case. For example, LiFePO4 batteries are known for their enhanced thermal stability and reduced risk of thermal runaway, making them a preferred choice for applications where safety is a primary concern, such as this project, which is designed for industrial applications.

However, despite their advantages, lithium-ion batteries also present certain considerations when implementing them. One notable concern is the need for active battery management systems (BMS) to prevent overcharging, over discharging, and thermal runaway, which can lead to dangerous situations such as explosion or fire. These BMS systems add complexity and cost to systems powered by lithium-ion batteries, which require careful monitoring and control of battery parameters to ensure safe and reliable operation.

Alongside this, lithium-ion batteries are susceptible to performance degradation over time, particularly in environments with high temperature or humidity. Factors such as cycling, depth of discharge, and ambient conditions can affect the lifespan and performance of lithium-ion batteries, necessitating proper maintenance and monitoring to optimize their longevity and efficiency.

Also of note, is that lithium ion batteries are generally more expensive than other rechargeable battery types. Their complex construction makes them a less economical choice compared to other battery chemistries available on the market.

With all these factors in mind, it can be seen that lithium-ion batteries offer advantages such as high energy density, low self-discharge rates, and availability in various chemistries such as lithium iron phosphate (LiFePO4). However, they also require external circuitry control systems to mitigate safety risks and can experience performance degradation over time. Consideration of these factors will determine what battery is most suitable for the Wrench Monkey.

Section 3.5.2: Sealed Lead Acid (SLA) Battery

Sealed lead-acid (SLA) batteries offer a few advantages and disadvantages depending on the application. One significant advantage is their low cost relative to other battery types, making them a simple solution for economical power storage. Additionally, SLA batteries feature a simple charging process, typically only requiring a constant voltage charger, which simplifies maintenance and operation. This ease of charging makes SLA batteries practical for an industrial use case, such as what Wrench Monkey is designed for. The capability to supply high power in short bursts, along with having high continuous current output, means they are suitable for demanding applications.

However, one notable drawback of SLA batteries is their relatively high weight and low energy density compared to other battery technologies like lithium-ion. The lead-acid chemistry used in SLA batteries results in a heavier and bulkier battery design, limiting their suitability for applications where weight and space constraints are important considerations, as is the case with our project. The low energy density of SLA batteries also means they provide less energy storage capacity overall, which has a net decrease on overall efficiency of the system.

Furthermore, SLA batteries are susceptible to performance degradation over time, particularly if subjected to high heat, deep discharges, or improper charging practices. This can result in reduced battery lifespan and premature wear, requiring regular maintenance and or complete replacement to ensure optimal performance.

Another consideration is the potential for electrolyte leakage in SLA batteries, which can occur if the battery is damaged or overcharged. This can pose safety hazards and environmental concerns, necessitating proper handling and disposal procedures to mitigate potential problems.

Despite these drawbacks, SLA batteries remain a popular choice for various applications. Their low cost, simple charging, and reliability make them a practical solution for various power storage needs, particularly in situations where weight and space constraints are not critical factors.

Section 3.5.3: Nickel-Cadmium Battery

Nickel-cadmium (NiCd) batteries offer several characteristics that can be advantageous depending on the use application. One significant advantage is their ability to withstand frequent charging and discharging cycles, making them highly durable and reliable. NiCd batteries are known for their robust construction and resistance to overcharging and deep discharging, which contributes to their long lifespan and consistent performance over time.

Moreover, NiCd batteries feature a fast charging capability, allowing them to be rapidly recharged compared to other battery types. This fast charging ability makes NiCd batteries well-suited for applications where quick turnaround times are essential, such as industrial robotic systems like the Wrench Monkey.

Additionally, NiCd batteries exhibit stable performance over a wide range of temperatures, making them suitable for use in extreme environmental conditions. This thermal stability enhances the versatility and reliability of NiCd batteries, allowing them to operate effectively in diverse applications and environments.

However, one notable drawback of NiCd batteries is their susceptibility to the memory effect, which can occur if the batteries are not fully discharged before recharging. The memory effect causes the battery to "remember" its previous state of charge, leading to reduced capacity and performance over time. To mitigate the memory effect, NiCd batteries require periodic deep discharges to maintain optimal performance, which can be inconvenient and time-consuming.

Furthermore, NiCd batteries have a lower energy density compared to other battery chemistries, resulting in a relatively bulky and heavy design. This limits their suitability for applications where weight and space constraints are important considerations. NiCd batteries also contain a toxic element, cadmium, which poses environmental and health hazards if not properly disposed of or recycled. The presence of cadmium in NiCd batteries requires careful handling and disposal procedures to minimize environmental impact and ensure compliance with regulations. Careful consideration of these factors is essential when selecting NiCd batteries for use.

Section 3.5.4: Battery Comparison and Selection

In regards to the selection of a power source for the Wrench Monkey project, an SLA (sealed lead-acid) battery became the definitive choice, primarily due to a combination of reliability and cost-effectiveness. Given the project's emphasis on durability, the robust nature of SLA batteries stands out compared to the other discussed battery chemistries. This characteristic not only contributes to the overall dependability of the Wrench Monkey but also aligns seamlessly with the project's objectives of optimizing efficiency and operation, which are heavily affected by the reliability of the power source.

Most importantly, the cost-effectiveness of SLA batteries further solidified their position as the chosen power source for the Wrench Monkey. This characteristic ensures extended operation without the financial burden, allowing the Wrench Monkey to function efficiently without the need for frequent replacements. Such reliability and endurance are very important considerations, particularly in industrial environments where sustained performance is essential for meeting operational demands effectively.

Despite the comparatively higher weight associated with SLA batteries when compared to the alternative lithium-ion or nickel-cadmium (NiCad) batteries, the emphasis on cost reduction outweighed other factors in the selection process. While lithium-ion and NiCad batteries offer lighter weight and higher energy density, their higher costs compromise the overall budget of the Wrench Monkey. In this context, the lower cost of SLA batteries is justified, as their reliability and robustness directly contribute to the project's operational goals.

Furthermore, the decision to opt for SLA batteries over NiCad batteries is due to considerations about charging requirements. While SLA batteries require simpler charging processes, NiCad batteries are plagued by the “memory effect,” where incomplete discharges result in decreased battery capacity over time. Such limitations are unacceptable in an industrial environment, for which the Wrench Monkey is designed.

Although the integration of SLA batteries necessitates accommodating their heavier weight, the benefits they offer in terms of cost-effectiveness and reliability far outweigh these additional requirements. Ultimately, the selection of SLA batteries is based on maximizing the performance, efficiency, and longevity of the Wrench Monkey. The table below shows some of the comparisons made to determine the viability of each battery type for the project.

Battery Type	Cost	Weight	Energy Density	BMS Required
Lithium-Ion	$30+	< 1 kg.	150-200 Wh/kg.	Yes
Sealed Lead-Acid	$20-25	1-2 kg.	30-50 Wh/kg.	No
Nickel-Cadmium	$20-25	1-2 kg.	40-60 Wh/kg.	No

Table 6: Battery Comparison

Section 3.6: Line Detection Sensors

There are multiple different ways in which a line can be detected for a line following robot. The following section compares color sensors, camera sensors, and IR sensors to identify the best choice to use in the Wrench Monkey project.

Section 3.6.1: Color Sensor

Color sensors being used for the line following system of the Wrench Monkey project offer several advantages that must be considered. One significant advantage is their versatility in detecting multiple colors accurately, which facilitates the complex navigation strategy we are planning on implementing between workstations. This capability allows the Wrench Monkey to differentiate between the various paths that will be present in the planned work area.

Notably, color sensors are typically available at a relatively low cost, making them an economical solution for line following applications. This affordability contributes to the overall cost efficiency of the Wrench Monkey project, allowing for the integration of multiple sensors within the given budget constraints.

Additionally, color sensors provide high precision and accuracy across the visible light spectrum, ensuring stable and reliable control of the robot's movement. This precision, coupled with a suitable control scheme, enables the Wrench Monkey to maintain optimal alignment with the desired path, minimizing deviations and errors during navigation.

However, color sensors also have a few important drawbacks. One notable drawback is their dependency on external lighting conditions for accurate color detection. Ambient light or additional light sources may be required to ensure adequate illumination for the sensors to function effectively, particularly in environments with varying lighting conditions or low light levels. This reliance on external lighting can pose challenges in industrial environments where lighting conditions may fluctuate unpredictably.

Furthermore, for stable control and reliable line following, at least two color sensors are typically necessary to detect both edges of the line. This increases the complexity and cost of the system, as multiple sensors must be integrated to ensure proper operation of the system.

Moreover, color sensors may be susceptible to interference from too bright ambient light, which can affect their accuracy and reliability. Additionally, calibration and fine-tuning may be required to optimize sensor performance and minimize false detections, adding complexity to the setup and maintenance process.

So, while color sensors offer advantages such as multi-color detection, low cost, precision, and accuracy, they also come with considerations such as dependency on external lighting, the need for multiple sensors, and susceptibility to interference.

Section 3.6.2: Camera Sensor

Utilizing a camera for line following in the Wrench Monkey is another possibility. One significant advantage is the higher fidelity provided by a camera, allowing for more detailed and accurate detection of the line. Unlike color sensors, a camera can capture the entire field of view, enabling it to determine not only the presence of the line but also its angle and curvature. This enhanced sensing capability facilitates smoother control of the Wrench Monkey, enabling it to navigate curves and intersections with greater precision and agility. In addition to better navigation of different path geometries, there are also more opportunities to implement sophisticated tools such as image processing and computer vision. With the help of these two tools we would be able to more easily identify different colored paths and the center of the path for error signal calculation which would be used for the control system.

Additionally, cameras are becoming increasingly affordable and accessible, with a wide range of options available to suit various budgets and requirements. This accessibility makes it possible to integrate a camera-based line following system into the Wrench Monkey project without significantly exceeding budget constraints.

In terms of size cameras are generally larger than IR and color sensors. Despite their size, cameras would still be advantageous over the other sensors because only one camera would be required to accomplish the visual control task, whereas at least two IR/color sensors would need to be used.

However, using a camera for line following also presents certain drawbacks. One notable drawback is the higher cost compared to traditional color or IR sensors. Importantly, cameras typically require more advanced hardware and software components such as a microcontroller or single-board computer, to process and analyze the camera feed in real-time. This increased computational complexity adds to the overall system complexity and may require additional resources for development and integration, resulting in a higher overall system cost.

Moreover, cameras may be susceptible to environmental factors such as lighting conditions, glare, and shadows, which can affect their performance and reliability. Proper calibration and tuning may be necessary to optimize camera performance and ensure accurate line detection under varying conditions.

Section 3.6.3: IR Sensor

Utilizing simple IR reflector sensors for line following in the Wrench Monkey project is another possible choice. One significant advantage is the simplicity of the sensor design, consisting of only an IR emitter LED and an IR receiver. This simplicity makes interfacing with the sensor very straightforward, as it typically has only two possible outputs - on or off - simplifying integration into the Wrench Monkey's control system.

Moreover, IR reflector sensors are available at a very low cost, making them a cost-effective solution for line detection applications. Their affordability allows for the integration of multiple sensors, as two would be required to properly function. This provides redundancy and reliability in line following tasks. IR reflective sensors also offer fast response times, enabling rapid detection of changes in surface reflectivity. This responsiveness facilitates real-time adjustments to the Wrench Monkey's trajectory using a given control scheme

However, using IR reflector sensors for line following also presents certain drawbacks. One notable limitation is their reliance on surface reflectivity to detect the line. IR reflector sensors can only detect dark surfaces that absorb IR light, such as black lines on a white background. This limitation restricts their applicability in environments with light-colored or reflective surfaces, where contrast between the line and the background may be insufficient for reliable detection.

Furthermore, IR reflector sensors may be susceptible to interference from ambient IR radiation sources, such as sunlight or artificial lighting. This interference can affect sensor performance and reliability, leading to false detections or erratic behavior.

Importantly, the range of IR reflector sensors is limited, which requires careful placement and alignment to ensure optimal detection of the line. Additionally, environmental factors such as dust can impact sensor performance and require periodic inspection maintenance to ensure consistent operation in an industrial application.

With this in mind, while IR reflector sensors offer advantages such as simplicity, low cost, and fast response times, they also come with considerations such as limited detection range, susceptibility to interference, and reliance on surface reflectivity for line detection. These factors are very important to balance when considering IR reflector sensors for line following in the Wrench Monkey project.

Section 3.6.4: Line Detector Sensor Comparison and Selection

In the selection process for the line detection sensor system of Wrench Monkey, the decision was initially going to be based on the fidelity and precision which pointed to the decision to use a camera module. However, after further research, it was determined that attempting to use the camera module for computer vision to detect the path line would not be as feasible for implementation for various reasons. Firstly, OpenCV, the main library for writing real-time computer vision programs, is too large for the ESP32 to handle. For this reason, there have been projects that others have done which clone and modify OpenCV to decrease the needed memory for operation; however, these modified versions of OpenCV then do not have the same flexibility as the official version which is needed for Wrench Monkey and are not as well-documented. In similar efforts to the more compact versions of OpenCV being created, there have been projects which send the images via Wi-Fi to a main computer which does the computer vision processing. Despite the attractiveness of being able to indirectly implement computer vision using the Wi-Fi capabilities of the ESP32, this would then add to the overhead of the control process which could compromise the line following capabilities at lower speeds as compared to other line follower robots. Since the ESP32 would also have to be using Wi-Fi to stay connected to the main website, this option would either be very difficult to implement or not possible.

Not only is the implementation of OpenCV more difficult due to the memory constraints, but learning to use the available tools to implement it would lead to longer development time for an approach that is more likely to have issues. More specifically, not only would we need to understand some of the basics of computer vision for line following, but we would also need to adapt the code for the compact version to be compatible with the hardware that we would be using.

Since the camera option is not as easily implementable, the two options left would be either the color sensors or the infrared sensors. One major difference between these two sensors is their outputs–IR sensors usually output either digital high or digital low (1 or 0), whereas color sensors usually output a range of values for the different color components. That being said, if the color sensors are not carefully calibrated, it could lead to incorrect color measurements and possibly cause Wrench Monkey to go off the path. Nevertheless, the color sensors could also have an advantage over the IR sensors if they are correctly calibrated because they could then be used to look for color markers to determine when to turn and they could possibly be used for a wider variety of surfaces than IR sensors.

On the other hand, the IR sensors also have to be calibrated, but the calibration process is much simpler in that the potentiometers can be quickly adjusted to give the desired readings. If the surfaces in which Monkey Wrench is operating are reflective of the infrared light (except the path of course), then there are no problems, but in the case of infrared absorbing terrain, there could be problems with the line following. To fix the problem of non-reflective terrain, a white background surface could be included as part of the path, but this would not be as convenient as simply placing tape in the desired path. Another drawback to using IR sensors would be the need to use them in conjunction with another sensor type such as an RFID reader (or even a color sensor) to detect when to turn into another branch of the path.

Despite the IR sensor array being the most costly, in terms of quick implementation it would be worth buying the IR sensors since they are more easily calibrated and they have already been widely used for line-follower robots which makes troubleshooting easier since more resources are available. Additionally, an RFID reader is used in conjunction with the IR sensor to determine at what points in the path that Wrench Monkey needs to turn.

Line Detection Sensor	Power/IO Pins Required	Cost
Color	4-8	$7.00
Camera	18	$8.99
IR (sensor array)	7	$11.98

Table 7: Line Detection Sensor Comparison

Section 3.7: Chassis Base Material

The following section describes the different materials considered while in search of a base material for the chassis.

Section 3.7.1: Wood

Wood being used as the chassis base construction material for the Wrench Monkey project is a very strong consideration. One significant advantage is its high strength-to-weight ratio, allowing for a sturdy and durable chassis while keeping overall weight relatively low. This lightweight design enhances the maneuverability and energy efficiency of the Wrench Monkey, prolonged operation on a single charge.

Moreover, wood is readily available and cost-effective compared to alternative materials such as metal, plastic, or composite materials like carbon fiber. Its affordability makes it an attractive option for prototype development or lower-budget projects like the Wrench Monkey, minimizing prototyping and production costs without compromising structural integrity. Since wood is relatively easy to work with and manipulate, this allows for customization and modification to suit specific design requirements. This flexibility in fabrication enables rapid prototyping and iterative design improvements, accelerating the development process.

However, using wood as the chassis base construction material also presents certain drawbacks. One notable limitation is its flammability, which poses a safety risk, especially in industrial environments where fire hazards must be mitigated. Proper fire-resistant coatings or treatments may be necessary to minimize the risk of ignition and ensure compliance with safety regulations.

Furthermore, wood is susceptible to environmental factors such as moisture, humidity, and temperature fluctuations, which can lead to warping, swelling, or decay over time. These issues may compromise the structural integrity and longevity of the chassis, potentially requiring replacement or other protective measures to prevent deterioration.

Similarly, compared to metals or composites, wood may have lower impact resistance and durability, particularly in high-stress or heavy-duty applications. This may limit the suitability of wood for tasks that require extreme load-bearing capacity or resistance to mechanical wear and tear. While wood offers advantages such as high strength-to-weight ratio, affordability, and ease of fabrication, it also comes with considerations such as flammability, susceptibility to environmental factors, and potential limitations in durability and impact resistance. Careful evaluation of these factors is essential if wood is selected as the chassis base construction material for the Wrench Monkey project.

Section 3.7.2: Aluminum

Aluminum metal being used for the chassis base construction of the Wrench Monkey project offers several advantages and drawbacks. One significant advantage is its combination of high strength, low weight, rigidity, and durability. Aluminum's excellent strength-to-weight ratio allows for a sturdy yet lightweight chassis, enhancing the maneuverability and energy efficiency of the Wrench Monkey. Its inherent rigidity ensures structural integrity, providing stability and reliability during operation. Additionally, aluminum exhibits exceptional durability, capable of withstanding mechanical stresses and impacts expected to be encountered within industrial environments.

Notably, aluminum is highly resistant to oxidation when exposed to humidity and temperature variations, making it suitable for use in diverse environmental conditions. This corrosion resistance ensures long-term performance and longevity of the chassis, minimizing maintenance requirements and prolonging service life. Additionally, aluminum offers excellent thermal conductivity, facilitating efficient heat dissipation during operation. This thermal management capability helps prevent overheating of internal components, ensuring optimal performance and reliability under sustained operation.

However, using aluminum metal for the chassis base construction also presents certain drawbacks. One notable limitation is its higher price compared to alternative materials such as plastic or wood. The cost of aluminum and the machining hardware required for fabrication increases the overall production expenses, which might be unsuitable for a given budget constraint

Furthermore, machining aluminum requires specialized equipment and expertise, adding complexity and time to the fabrication process. The need for precision machining and finishing results in less time to dedicate to other parts of the project, along with higher production costs compared to materials that are easier to work with, such as wood or plastic. With these in mind, while aluminum offers advantages such as high strength, low weight, corrosion resistance, and thermal conductivity, it also comes with considerations such as higher cost, machining complexity, and lower impact resistance.

Section 3.7.3: Plastic

Utilizing a plastic chassis base for the Wrench Monkey project offers several advantages and drawbacks. One significant advantage is its high strength and rigidity, which allows for a sturdy and stable chassis construction. Plastic materials such as ABS or polycarbonate can provide sufficient structural support for the Wrench Monkey, ensuring reliable operation in various environments.

Importantly, plastic chassis bases offer excellent impact resistance, capable of absorbing and dispersing energy from collisions or mechanical shocks without lasting deformation. This impact resistance helps protect internal components and ensures the durability of the Wrench Monkey, reducing the risk of damage during operation.

Additionally, plastic chassis bases are lightweight compared to metal alternatives, contributing to the overall agility and maneuverability of the Wrench Monkey. The lightweight nature of plastic materials makes them suitable for applications where weight constraints are of concern, such as this project.

However, using a plastic chassis base poses a few cons to consider. One notable limitation is its lower strength-to-weight ratio compared to materials like aluminum or wood. Plastic materials may require thicker walls or additional reinforcement to achieve the same level of structural integrity as metal or composite alternatives, potentially adding bulk and weight to the chassis.

Furthermore, plastic chassis bases may be susceptible to deformation under high loads or when exposed to elevated temperatures. Prolonged exposure to heat or mechanical stress can cause plastics to soften or warp, compromising the stability and functionality of the Wrench Monkey. Moreover, plastic materials may have limited resistance to certain chemicals or environmental factors, which can lead to degradation or discoloration over time. This may necessitate protective coatings or treatments to maintain the appearance and performance of the chassis base. Careful evaluation of these factors is essential if selecting a plastic chassis base for the Wrench Monkey project.

Section 3.7.4: Carbon Fiber

Carbon fiber being used for the chassis base of the Wrench Monkey project offers several advantages. One significant advantage is its exceptionally high strength-to-weight ratio, making it one of the strongest and lightest materials available for chassis construction. Carbon fiber's unparalleled strength allows for a robust and durable chassis while keeping overall weight to a minimum, enhancing the agility and energy efficiency of the Wrench Monkey.

Moreover, carbon fiber exhibits outstanding durability and stability in industrial environments, as it is resistant to heat, humidity, and corrosion. This resilience ensures long-term performance and reliability of the chassis, even in harsh operating conditions, like industrial environments, minimizing maintenance requirements and downtime. Additionally, carbon fiber offers excellent stiffness and rigidity, providing high structural support for the Wrench Monkey's components, namely the battery and tool chest. Its inherent stiffness helps maintain stability during operation, ensuring smooth movement along designated paths.

Furthermore, carbon fiber can be molded into complex shapes and configurations, allowing for customizable designs to meet specific project requirements. This flexibility in fabrication enables the creation of lightweight yet robust chassis structures tailored to the Wrench Monkey's unique needs.

However, using carbon fiber for the chassis base also presents certain drawbacks. One notable limitation is its very high cost compared to traditional materials such as metal or plastic. The expense associated with carbon fiber production and processing may significantly impact project budget constraints, making it less feasible for a budget-conscious project like the Wrench Monkey.

Importantly, carbon fiber can be challenging to machine and work with due to its hardness and abrasiveness. Specialized equipment and expertise are required for cutting, shaping, and finishing carbon fiber components, adding complexity and cost to the fabrication process. So, while carbon fiber offers advantages such as high strength-to-weight ratio, durability, and stability, it also comes with considerations such as high cost, difficulty in machining, and limited availability. Careful evaluation of these factors is essential when considering carbon fiber for the chassis base of the Wrench Monkey project.

Section 3.7.5: Chassis Base Material Comparison and Selection

While considering the pros and cons for each chassis material for the Wrench Monkey project, wood emerged as the optimal choice, driven by its affordability and ease of manipulation. While the alternatives such as plastic, aluminum, and carbon fiber were considered, the inherent advantages of wood outweighed the competing materials. Notably, wood's remarkably low price and accessibility made it a superior option given the project's budgetary constraints.

One of the key factors influencing the decision was wood's ease of manipulability with basic hand and power tools. Unlike the more rigid and specialized nature of aluminum or carbon fiber, wood is much easier to form to a desired shape. Sanding, cutting, and drilling, can be done very easily compared to the other materials. This attribute simplifies fabrication and allows prototypes to be iterated on quickly

Despite not being the strongest or most durable material among those considered, wood offers sufficient strength for the intended application in the project. The structural integrity provided by wood is more than adequate to support the operational requirements of the Wrench Monkey, ensuring reliability while operating. Additionally, the versatility of wood allows for additional reinforcement or customization to be added easily as needed, enhancing its suitability for design specifications that can change.

Another significant advantage of wood is its widespread availability and ease of acquisition. Unlike aluminum or carbon fiber, which may require specialized suppliers or manufacturing processes, wood is readily accessible and can easily be sourced locally. Additionally, wood can be easily cut to fit at a supplier, reducing the need for expensive machining or fabrication processes and therefore expedites the prototyping and construction timeline.

In summary, the selection of wood as the chassis material for the Wrench Monkey was based on balancing cost-effectiveness, ease of fabrication, and structural suitability. While it may not boast the same strength-to-weight ratio as aluminum or the high-tech appeal of carbon fiber, wood's affordability, manipulability, and accessibility make it an ideal choice for realizing the project's objectives. The table below outlines the factors that were considered when choosing the material to use.

Chassis Base Material	Cost	Shear Strength	Ease of Manipulability
Wood	< $10	1.9 MPa	High (Hand Tools)
Aluminum	$200+	207 MPa	Low (Machining)
Plastic	$50+	100-150 MPa	Medium (Hand Tools)
Carbon Fiber	$1200+	590 MPa	Low (Machining)

Table 8: Chassis Base Material Comparison

Section 3.8: Microcontrollers & Single-Board Computers

Microcontrollers and single-board computers play a crucial role in modern robotics and embedded systems. They provide the computational power and connectivity needed to control devices, process data, and interact with the environment. Each type of device offers unique capabilities and features, making them suitable for different tasks within the project's requirements. In this section, we will explore three popular options: the ESP-32S microcontroller, the Raspberry Pi 4 Model B single-board computer, and the Arduino Uno R4 WiFi microcontroller. We will go over the strengths, limitations, applications in robotics, and how they relate to the Wrench Monkey project.

Section 3.8.1: ESP-32S

The ESP-32S microcontroller, part of the ESP32 series developed by Espressif Systems, is known for its versatility and capabilities in the realm of embedded systems and electronics related hobby projects. One of the key advantages of this microcontroller is its powerful dual core Xtensa LX6 chipset which operates at a clock speed of up to 240MHZ. This high processing power enables the microcontroller to handle complex tasks with ease, making it suitable for controlling the various functionalities of the Wrench Monkey. This microcontroller can handle managing motor movements, processing sensor data, or handling communication protocols such as I2C or UART, contributing to the overall performance of the robot.

The ESP-32S also has 32 GPIO pins allowing for an ample amount of sensors, actuators, and external modules which may be implemented for this project. The pins can be utilized not only for basic interfacing but also for advanced functionalities like detecting environmental parameters using data from ultrasonic sensors for object avoidance. Beyond that, the ESP-32S offers versatile connectivity options including Wi-Fi and Bluetooth. This is extremely useful for this project as the robot must be able to send and receive data from a server via a full stack deployment.

Overall, the ESP-32S microcontroller offers a comprehensive solution that aligns well with the design requirements of the Wrench Monkey project. Its combination of processing power, GPIO flexibility, and connectivity options makes it a valuable component for completing all of Wrench Monkey’s tasks efficiently.

Section 3.8.2: Raspberry Pi 4B

The Raspberry Pi 4 Model B, developed by the Raspberry Pi Foundation, stands out as a high performance SBC, or single-board computer, that is well-suited for a wide variety of projects. Unlike the ESP-32S microcontroller, which excels in embedded systems with its specialized features, the Raspberry Pi 4 Model B offers a full-fledged computing platform with expanded capabilities. One of the key advantages of this single-board computer is its powerful Broadcom quad-core ARM processor, running at up to an amazing 1.5GHz. The processing power enables the computer to handle extremely demanding tasks such as web browsing, data analysis, complex algorithms, and image processing. While these capabilities may be considered excessive for the Wrench Monkey’s requirements, they showcase the versatility and performance of the Raspberry Pi 4.

In addition to its processing power, the Raspberry Pi 4 supports dual 4K displays via micro HDMI ports and can interface with several Raspberry Pi branded cameras. This is unnecessary for the Wrench Monkey project as the device only needs to be interfacing with the full stack deployment, but the added community support and documentation for the camera options would make future line detection operations trouble-free. Another notable feature of this single-board computer is the option for expandable memory. While the board itself does not come with a microSD card unless purchasing a bundle option, it supports microSD card sizes ranging from 8GB to a massive 2TB, providing ample storage for data and applications.

Beyond its hardware capabilities, the Raspberry Pi 4 offers the flexibility to load operating systems on board instead of interfacing via serial commands. The wide range of operating systems include many popular Linux distributions like Ubuntu or Debian as well as a scaled-down version of Windows. This versatility extends to a variety of programming languages and development environments, making it accessible to a diverse range of developers and hobbyists.

In summary, while some features of the Raspberry Pi 4 Model B may exceed the design constraints of the Wrench Monkey project, its robust computing platform, advanced capabilities, expandability options, and extensive community support make it a valuable complement to the ESP-32S microcontroller.

Section 3.8.3: Arduino Uno R4 WiFi

The Arduino Uno R4 WiFi is an iteration of the popular Arduino Uno series. This device introduces built-in Wi-Fi connectivity utilizing an ESP32-based chip. Unlike the ESP-32S microcontroller and the Raspberry Pi 4 Model B, which offer extensive processing power, the Arduino Uno R4 WiFi focuses on simplicity, ease of use, and real-time control in embedded systems.

Key specifications of this microcontroller include an Arm Cortex-M4 processor operating at 48MHz, providing sufficient computational power for real-time control and basic processing tasks. While its processing capabilities may not match that of the previous two choices, the Arduino Uno compensates with its simplicity and ease of programming, making it accessible to beginners and experienced users alike. With 20 GPIO pins, this Arduino offers a degree of flexibility when interfacing with sensors, actuators, or other external modules when compared to the other two options.

Additionally, this version of the Arduino Uno introduces on-board peripherals such as a 12-bit DAC, CAN BUS, and variable OP AMP, expanding its capabilities with electronics projects. The extended 24 volt tolerance makes it suitable for integrating with motors, LED strips, and other actuators using a single power source.

In summary, the Arduino Uno R4 WiFi strikes a balance between simplicity, functionality, and connectivity making it an excellent choice for projects requiring real-time control and wireless communication while maintaining compatibility with existing Arduino hardware and software. Its user-friendly design, extended documentation, and affordable price point make it a valuable addition to hobbyists and professionals alike.

Section 3.8.4: Microcontroller Comparison and Selection

After comparing the different options and weighing the pros and cons of each microcontroller, it was ultimately decided to use the ESP-32S microcontroller in the wrench monkey as it provided efficient GPIO pins, as well as a built-in wifi capability. It is also the cheapest option available, which helps keep the overall project costs lower.

Microcontroller/ Single-Board Comp.	GPIO Pins	Serial Communication	Connectivity	Cost
ESP-32S	32	I2C, I2S, SPI, UART	Wi-Fi, Bluetooth Classic, BLE	6.00 USD
Raspberry Pi 4 Model B	40	UART, SPI, I2C	Wi-Fi Dual Band, Bluetooth Classic, BLE, Ethernet	75.00 USD
Arduino Uno R4	20	UART, I2C, SPI, CAN	Wi-Fi, Bluetooth Classic, BLE	27.50 USD

Table 9: Microcontroller & Single-Board Computer Selection

Section 3.9: Part Selection

The engineering specifications and constraints emerged were the primary factors in the process of selecting part technologies for the Wrench Monkey, with size, weight, and power requirements having the most significant influence. The compact footprint of the chassis, measuring just 1 foot by 2 feet, served as the primary constraint that heavily shaped the selection of parts throughout the project. Every component chosen has to adhere to differing size limitations to ensure integration within the confined space of the Wrench Monkey chassis.

As such, the sizing of each part was a primary factor in determining the suitability of various parts for the project. Components had to be compact enough to fit within the constrained dimensions of the chassis without compromising functionality or performance. This required evaluation of each part's physical footprint and form factor to ensure efficient utilization of space and optimal layout within the Wrench Monkey's design.

Moreover, the implemented weight constraints posed another significant challenge that directly influenced part technology selection. Additional parts or heavier parts being added to the Wrench Monkey had potential repercussions on its agility, maneuverability, and energy efficiency. As such, lightweight part technologies were prioritized for the chassis to maximize operational performance. Motors, batteries, and sensors were each researched for their respective weight contribution, with preference given to solutions that offered a favorable balance of performance and weight efficiency.

Additionally, the power requirements played an important role in determining the viability of part technologies for the Wrench Monkey. With power being limited by the on-board battery, every component had to be selected with careful consideration of its power consumption and efficiency. Energy-efficient designs and lower-power versions were prioritized to ensure optimal utilization of available power capacity, which in turn extends the operational runtime.

Section 3.9.1: Chassis Material

In our team's research for the most suitable material for our chassis, a comprehensive comparison between plywood and oriented strand board (OSB) was made, and attributes of each material type were considered. After our research, it became apparent that birch plywood could easily meet our project's specific requirements, primarily due to its combination of strength, versatility, and low cost.

One of the primary factors in favor of plywood is its structural integrity, stemming from its composition of adhered sheets of wood. This layered construction gives plywood exceptional durability and resilience, making it capable of withstanding significant loads and stresses without deformation or total failure. In contrast, OSB, constructed from adhered strips of scrap wood, lacks the cohesive strength and stability compared to plywood, rendering it inherently less robust and more prone to structural failure.

Moreover, the easier machinability of plywood proved to be a critical consideration in our material selection process. Unlike OSB, which presents significant challenges during fabrication due to its fragile nature, plywood lends itself to machining without breaking. Drilling, cutting, and sanding are common modifications expected to be performed while prototyping and assembling Wrench Monkey, and OSB is more likely to break when these tasks are performed. This inherent workability of plywood not only makes our production process easier but also minimizes the risk of errors like cracking/breaking, which would require purchasing of new wood.

The denser composition of plywood compared to OSB further makes it the preferred chassis material, giving it higher rigidity and stability. This structural integrity not only reinforces the overall strength of our design but also provides a solid foundation for supporting the additional components like the battery and tools themselves. As a result, the inherent stiffness of plywood further mitigates the risk of mechanical failure or structural compromise.

Additionally, plywood's high resistance to warping, moisture ingress, and environmental degradation improves its suitability for our application, which is intended for use in industrial environments where humidity and temperature fluctuate. Unlike OSB, which may succumb to warping or degrade when exposed to moisture or fluctuating environmental conditions, plywood maintains its shape and structural integrity over time, ensuring the longevity and reliability of the chassis in diverse operating environments.

Beyond these advantages, plywood offers a slew of other benefits, including a smoother surface finish for enhanced aesthetics and ease of handling and transportation due to more rigid structure. By selecting birch plywood as our chassis material, the Wrench Monkey's chassis strength, durability, and reliability increases. The table below gives a few of the factors compared between the two wood types.

Image 3.1: Plywood Board Used

Chassis Material	Cost	Compression Strength	Density
Plywood	$9	3,000-5,000 PSI	39.6 lb/cuft
OSB	$5	1,000-1,500 PSI	37.5 lb/cu.ft

Table 10: Wood Selection

Section 3.9.2: Battery Type

In our search for battery options for our project, we boiled down the comparison between a 12V 4Ah battery and a 12V 7.2Ah battery. We researched the offerings from 2 different brands: the 4Ah battery from Casil priced at $21.99 and the 7.2Ah battery from Mighty Max Battery priced at $19.99. Both batteries utilize the same LiFePO4 chemistry, ensuring comparable performance and reliability for our project.

One of the primary factors weighed in our decision is the capacity of each battery. While the Casil 4Ah battery obviously has a lower capacity compared to the Mighty Max Battery 7.2Ah battery. This higher capacity of the 7.2Ah battery presented an advantage as well as being cheaper, allowing us to achieve our desired operational runtime for a lower price.

Despite the larger footprint and slightly heavier weight of the 7.2Ah battery, measuring at 5.94 x 2.56 x 4.07 in. and weighing 4.5 lbs compared to the 2.7 lbs and dimensions of 3.58 x 2.76 x 3.94 in. for the 4Ah battery, the cost-effectiveness and increased capacity of the former made it the more viable option for our project. The larger capacity helps ensure extended operation between charges. Furthermore, the lower price point of the 7.2Ah battery from Mighty Max Battery makes it a more desirable choice without compromising on quality or performance. This emphasis on affordability aligns with our project's budgetary constraints and economically-conscious design efforts.

The physical characteristics of the batteries, such as size and weight, played the most significant role in our decision-making process. While the 7.2Ah battery may have a larger footprint and weigh slightly more than the 4Ah counterpart, these differences are outweighed by the benefits it offers in terms of capacity and cost-effectiveness. The slight increase in size and weight is a reasonable trade-off for the extended runtime and overall performance gains achieved with the 7.2Ah battery.

Additionally, the cost analysis is a very important aspect of our decision-making process. Because of the marginal price difference between the two batteries, the lower cost of the 7.2Ah battery from Mighty Max Battery makes it a better choice. This cost-saving opportunity allows us to invest in other areas of the project to further enhance its capabilities.

In essence, the decision to opt for the 12V 7.2Ah battery from Mighty Max Battery over the 12V 4Ah battery from Casil was driven by a careful consideration of factors such as power capacity, cost, size, and overall suitability for our project's requirements. By leveraging the higher capacity and cost-effectiveness of the 7.2Ah battery, we are able to achieve optimal performance and longevity to allow the Wrench Monkey project to realize its full potential. The table below shows the main comparison points considered when choosing the battery to be used.

Image 3.2: Mighty Max Battery Used

Battery Choice	Cost	Capacity	Footprint	Weight
Casil	$21.99	4Ah	3.58 x 2.76 x 3.94 in.	4.5 lbs
Mighty Max	$19.99	7Ah	5.94 x 2.56 x 4.07 in.	2.7 lbs

Table 11: Battery Selection

Section 3.9.3: Motor Type

In our team’s assessment of motor options for the Wrench Monkey project, the comparison boiled down to determination between the CQRobot Ocean 12V DC motor and the Walfront 12V DC motor for the propulsion system. Both motors offer a rotational speed of 40RPM at the given voltage and are both equipped with encoders, ensuring precise control and feedback in our application. However, upon comprehensive evaluation, several key distinctions emerged that lead to the selection of the CQRobot motor over the Walfront motor.

One of the primary considerations in our decision-making process was the torque capability of each motor. While both motors deliver a similar rotational speed, the CQRobot motor stands out with its superior torque rating of 70kg.cm compared to the Walfront motor's 25 kg.cm. This higher torque capacity is essential for our project's requirements, as scenarios where increased force and power are necessary are expected, and torque is required to accomplish that

Furthermore, the mechanical design and gearbox setup of the motors played a crucial role in our decision. The Walfront motor's gearbox configuration was not ideal for Wrench Monkey, as the rotating shaft is perpendicular to the motor shaft.

This posed potential challenges in integration and alignment within our system. In contrast, the CQRobot motor's output shaft is parallel to the motor shaft, and mounting hardware is included. This offers a simpler and more efficient mechanical arrangement, making installation easier and reducing potential points of failure.

Moreover, the availability and quality of documentation for each motor were significant factors in our evaluation process. The CQRobot motor stood out as it has extensive documentation, including detailed specifications, dimensions of various components, and integration guidelines. This information allows a much simpler process to integrate the motor into our project, and allows efficient design and fabrication of mounting hardware, as there is no need to manually measure the dimensions of fixtures and of the motor itself and ensures compatibility with existing hardware.

Ultimately, the decision to opt for the CQRobot Ocean 12V DC motor over the Walfront motor was driven by a combination of factors, namely higher torque capabilities, superior mechanical design, and comprehensive documentation. By leveraging these advantages, we are confident in the reliability, performance, and versatility of the chosen motor, allowing the Wrench Monkey project to meet its expected objectives. The table below outlines the main characteristics of the motors considered when deciding on which one to use.

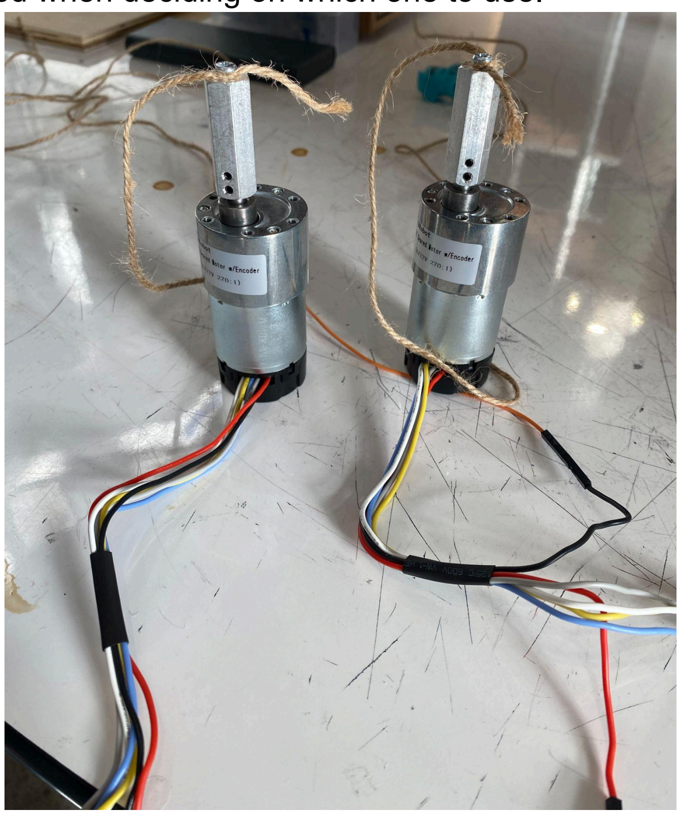

Image 3.3: Selected Servo Motors for Wrench Monkey

Motor Choice	Cost	Torque	Mounting Style	Documentation
CQRobot	$33	70kg.cm	Parallel	Yes (Wiki)
Walfront	$16	25kg.cm	Perpendicular	No

Table 12: Motor Selection

Section 3.9.4: Line Detector Sensor

In our search process for sensor options for the line detection aspect of the Wrench Monkey project, we narrowed down our choices to the HiLetGo individual IR sensors and the OSOYOO 5 IR sensor array. Each option presented distinct advantages and drawbacks, requiring a thorough evaluation to determine the most suitable solution.

The HiLetGo individual IR sensors offer a straightforward solution with breakout pins for connection to another microcontroller board. This simplicity can be advantageous, especially for projects where a separate microcontroller is already in use or preferred. However, it also means that each sensor must be individually wired, requiring more pins and additional hardware integration steps to incorporate the sensors into the overall system.

On the other hand, the OSOYOO 5 IR sensor array integrates multiple IR sensors into a single module, providing a more self-contained solution. While this integration can be convenient depending on the intended application, it introduces potential drawbacks, such as increased power consumption and complexity. Integrating this module with another microcontroller for the rest of the system functions also adds an additional layer of complexity and could impact overall system performance.

However, one notable advantage of having a dedicated sensor array, as seen in the OSOYOO module, is the potential to simplify the wiring and reduce the number of pins required. Managing multiple individual sensors can be cumbersome and resource-intensive, while an integrated array can streamline the design and improve efficiency. Not only simplify wiring, but using the IR sensor array also simplifies the mounting process by only requiring a simple mount to be made for the array.

We ultimately decided on utilizing the OSOYOO sensor array, due to the aforementioned benefits of simplified wiring and reduced pin requirements. Since it is crucial to have fast, accurate line detection, it makes sense to choose the option where a single subsystem can perform those operations, leaving the main controller to handle the rest of the system functions. The table below shows the main points considered when determining which sensor to use.

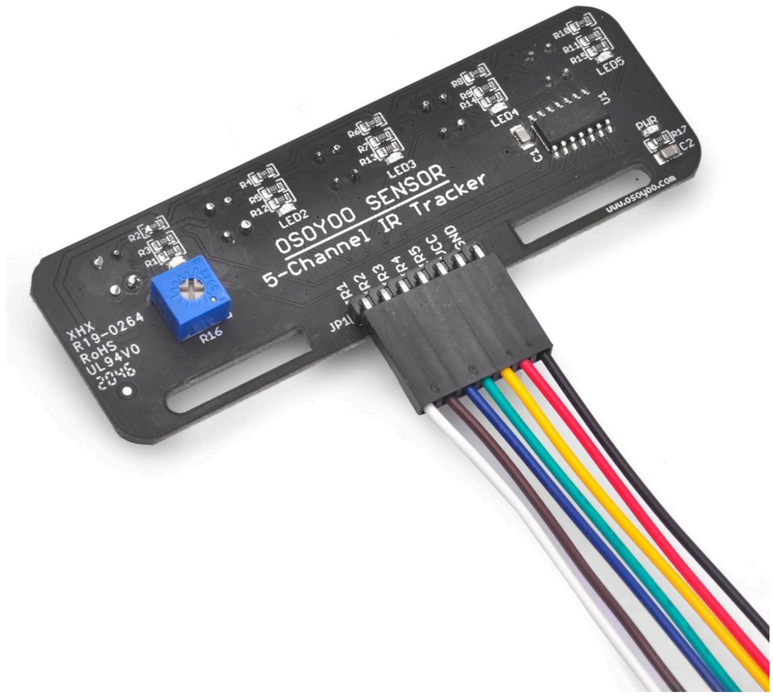

Image 3.4: Selected IR Sensor for Wrench Monkey

Sensor Choice	Cost	Pins Required
OSOYOO	$11.98	7
HiLetGo	$8.79	15

Table 13: Line Sensor Selection

Section 3.9.5: Tool Detection Sensor

In our pursuit of suitable components for the Wrench Monkey project, we conducted research to determine the most fitting resistive strain gauge. Recognizing the necessity for a form factor that could align along the tool slot's perimeter, we opted for a long, rectangular strip configuration.

Similarly, our selection process for the RFID sensor involved comprehensive analysis and evaluation. After identifying the RC522-based 13.56 MHz readers as the most suitable option due to their widespread usage and compatibility with our project objectives, we explored the diverse range of available alternatives. Despite the generic nature of these sensors, which offered a multitude of options, our decision-making was guided by a commitment to balancing functionality, compatibility, and cost-effectiveness.

Ultimately, our procurement strategy prioritized sourcing the most cost-effective components from reputable online vendors, ensuring that each component seamlessly integrated into the Wrench Monkey project while upholding professional standards of quality and performance.

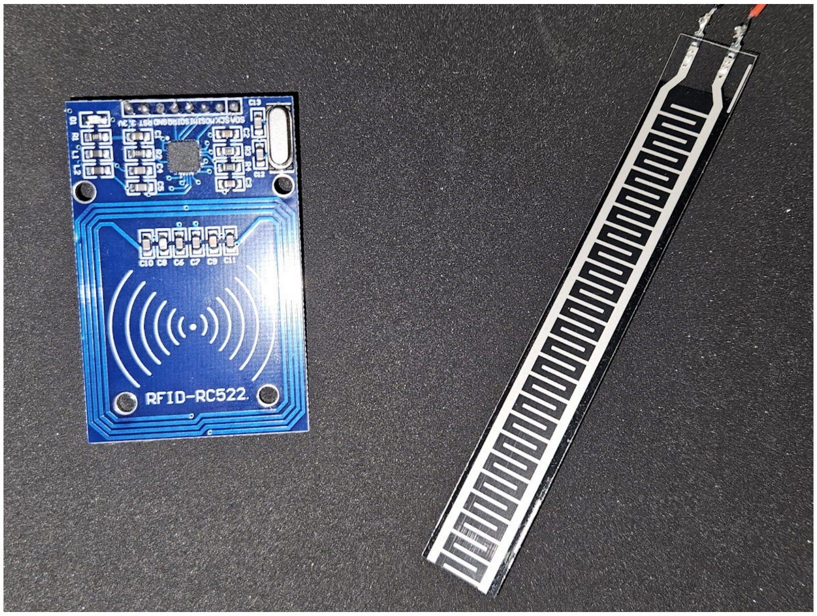

Image 3.5: RFID Reader and Thin Film Strain Gauge

Tool Detection	Cost	Pins Required	MTTF
HiLetGo RFID	$3.33	8	10+ years
Marhynchus Thin Film Strain Gauge	$6.00	2	2+ years

Table 14: Tool Detection Selection

Section 3.9.6: Control Processor Selection

After carefully examining the strengths, limitations, and applications of the ESP-32S microcontroller, Raspberry Pi 4 Model B single-board computer, and the Arduino Uno R4 WiFi microcontroller, the choice for the Wrench Monkey project becomes clear with the ESP-32S microcontroller standing out as the most suitable option.

The ESP-32S's versatile connectivity options including Wi-Fi and Bluetooth align perfectly with the project's requirement to send and receive data from a server via a full stack deployment. This connectivity combined with its energy efficiency and powerful dual-core Xtensa LX6 chipset operating at 240MHz, makes it an ideal choice for robotics and the Wrench Monkey project.

While the Raspberry Pi 4 Model B and the Arduino Uno R4 WiFi offer impressive features and capabilities such as expandable memory, additional peripherals, and a robust computing platform, they exceed the specific design constraints and requirements and sit at a much higher price point. The extended features of these two devices, while valuable in other contexts, may not be fully utilized or necessary for this particular project's objectives. The ESP-32S emerges as the optimal choice striking a balance between performance, flexibility, energy efficiency, and cost-effectiveness.

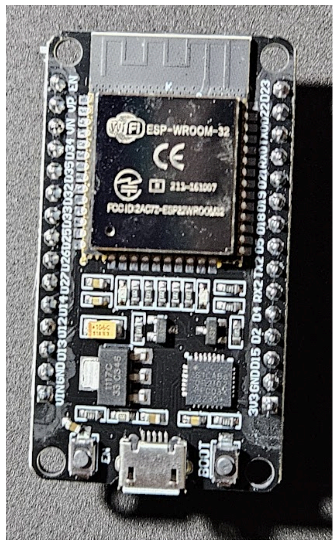

Image 3.6: ESP-32S Module Chosen

Controller/ Main Board	ESP-32S	Raspberry Pi 4 Model B	Arduino Uno R4 WiFi
Chipset	Dual-Core Xtensa LX6	Quad-Core Cortex A72	Arm Cortex-M4
Clock Speed	Up to 240MHz	1.8GHz	48MHz
GPIO Pins	32	40	20
Memory	4MB Flash, 520KB SRAM, 448KB ROM	Min 8GB SDRAM Max 1TB SDRAM	256KB Flash, 32KB SRAM, 8KB EEPROM
Serial Comms	I2C, I2S, SPI, UART	I2C, SPI, UART	I2C, SPI, CAN, UART
Connectivity	Wi-Fi, BLE	Wi-Fi Dual Band, BLE, Ethernet	Wi-Fi, BLE

Cost	6.00 USD	75.00 USD	27.50 USD

Table 15: Microcontroller & Single-Board Computer Selection

Chapter 4: Design Standards and Constraints

This section dives into the established standards and constraints that guide our project's course and influence our design decisions. Adhering to industry standards and integrating constraints is fundamental in crafting a project that is not only safe and reliable, but also efficient. The following chapter of the report provides an in-depth exploration on each relevant standard and thoroughly justifies the primary constraints imposed on the project.

Section 4.1: Project Standards

Standards are technical documents within engineering that are important to ensure the quality and reliability of a product or method, as well as the uniformity of specific processes. Without standards it would be difficult to ensure the quality of a product, and it would also make it difficult or impossible to integrate different technologies. Standards also ensure the safety of the manufacturers, as well as the users of the products, as there are safety requirements that have to be met and specific processes that have to be followed to ensure safe use.

There are many different types of standards, including voluntary, de facto, consortia, and regulatory to name a few. A VCS, or Voluntary Consensus Standard, is a standard developed by a group of representatives of any interested party and it is subject to due process to ensure that people agree on the standard. These VCS standards can be approved through the American National Standard, or ANS, which provides it with ANSI's unique accreditation of the procedure and oversight of the approval process. Another type of standard is a De Facto, or Ad Hoc standard, which is a standard that is not always officially approved, however it is simply widely used and recognized. A consortia standard is a more broad category that has approval processes much like the ANS approval process, however they can limit participation in the approval process if they choose to. The last type of standard to be described is a regulatory standard, which is a standard that is written by or adopted by governments, and therefore they are required to be followed by law. There are also other standards, such as those developed or adopted by individual companies.

There are multiple different organizations that can publish standards. One well known organization is the American National Standards Institute. It is a private, non-profit organization that works to publish voluntary consensus standards in the United States. Publishing a standard with ANSI ensures a neutral platform for development and discussion over standards, and ANSI also provides accreditation services to ensure that organizations operate according to the recognized standards and processes, which increases the credibility and reliability of their standards. The Institute of Electrical and Electronics Engineers, commonly referred to as IEEE, is another professional, non-profit organization that can help develop standards. Unlike ANSI, which covers a wide range of products and processes, IEEE focuses on developing technological standards that relate to electrical engineering, electronics, and computer science.

Another organization that is known for developing standards is the Robotic Industries Association, or RIA. As the name suggests, the standards that RIA helps to develop are focused on robotics, covering topics such as design, performance, safety, and programming. Underwriters Laboratory is an organization that develops safety standards for a wide range of industries. Something that makes UL unique is the fact that they have a long history of developing standards, and they are globally recognized and trusted, which provides standards developed by them an extra layer of credibility than some other organizations. IEC, or the International Electrotechnical Commission, is also a global organization that develops standards. IEC is also a globally recognized organization, and they tend to work with other national standards organizations, such as ANSI in the United States or the British equivalent, the British Standards Institution, also known as BSI, in the United Kingdom. This provides standards they produce to have the credibility that comes with approving standards through the national organizations, as well as an extra layer of credibility due to the two organizations working together.

The final organization to be discussed in this paper is IPC, which stands for the Institute for Printed Circuits. IPC is now known as the Association Connecting Electronics Industries, and it is a global trade association that focuses on developing standards within the electronics industry. IPC standards are often widely adopted and recognized worldwide and are known for their practicality and applicability to real-world challenges within the industry. All of the above organizations, as well as many others not listed here, help provide manufacturers and users with clear guidelines on many aspects of developing or using a product. Standards developed and published by these accredited organizations provide insight on aspects such as what materials to use, how to complete certain processes, how to make products compatible with each other, quality requirements, and safety requirements. This is beneficial to manufacturers and users alike as it allows them to ensure the safety, quality, and reliability of their products.

Section 4.1.1: Soldering Standard

IPC J-STD-001 was developed by the Association Connecting Electronics Industries, or IPC, to provide standards and requirements for the soldering processes and other aspects related to soldering. Originally published in 1992, this standard has undergone many revisions and updates to make sure that soldered joints are high quality and effective, as well as to ensure that users are completing these processes safely. Soldering is a process that joins two metal pieces together by melting solder between them. There are many different applications for soldering, many of which require clean, strong, precise connections between the parts. Because of this, it is important that there are standards in place to ensure the quality of the joints, as well as the safety of the users throughout the soldering process.

The IPC standard on soldering defines the approved manufacturing and inspection processes, as well as the approved materials that can be used. One requirement that is outlined in the standard is the importance of cleanliness. Cleanliness prevents the contamination of the materials being used, as well as the tools, ensuring the safe and effective use of these things in future products. The standard also specifies the required heating and cooling rates for different materials, and it emphasizes that the wires being soldered together cannot be damaged in any way as this could affect the quality of the connection. Should defects occur in the soldering process, the standard states that the customer's requirements will specify if it is acceptable to rework the product or if the manufacturer is to begin again with new materials, as the defect could affect the functionality of the product.

The standard is also equipped with a guide to show what the ideal solder looks like so that there is no ambiguity, as a defect could cause major issues if the job is not done properly. It specifies that the visual inspection requires both an automated optical inspection, or AOI, as well as an automated X-ray inspection, or AXI, before the product can be approved. The standard provides in depth details on how soldering is to be completed so that it is done safely and effectively.

It also provides details on how the solder is to be inspected and the requirements it has to meet to ensure its quality and effectiveness. Without this standard and other ones like it, there is a chance that beginner or experienced manufacturers alike could make a mistake, causing the final product’s functionality to be affected. This could happen by simply adding too much solder so that it comes into contact with a neighboring wire, pin, or pad, or adding too little solder so that the connection degrades over time and the connection between those parts is lost. Standards such as this provide customers the confidence that they are receiving a quality piece of work that will last.

The Wrench Monkey is equipped with one custom PCBs, as well as many sensors, so therefore it will require a decent amount of soldering. Because of this, this standard is important as it will ensure the safety of the team and users, as well as the quality of the soldered joints and the effectiveness of the design.

Section 4.1.2: Wi-Fi Standard

IEEE 802.11ax, which is also called Wi-Fi 6 is the latest standard for Wi-Fi which is preceded by six older Wi-Fi standards and will most likely be followed by IEEE P802.11be in the year 2024. The original IEEE 802.11 standard was developed by the IEEE Local Area Network Standards Committee (LMSC) in 1997. The purpose of this standard is to specify the protocols to be used when implementing wireless local area network (WLAN) computer communication. In addition to those basic outcomes from implementing IEEE 802.11ax, adhering to this standard also enhances the performance of the communication between devices in areas where there is a high Wi-Fi usage density such as schools, public events, etc. Another desirable characteristic offered by the implementation of this standard is increased data security to protect user information.

Since the Wrench Monkey is implemented using the ESP-32S microcontroller, the Wi-Fi transceiver will be operating at 2.4GHz. As previously mentioned, the Wi-Fi functionality is used on the ESP-32S to connect to a Wi-Fi network in order to receive internet connection. The workspace computers can access the internet to use the Wrench Monkey website to request desired tools.

Section 4.1.3: Industrial Mobile Robots Standard

ANSI/RIA R15.08 is a standard that was approved in 2020 and developed by the Robotic Industries Association, or RIA, working with the American National Standards Institute, or ANSI. This standard focuses on the design, integration, and use of industrial mobile robots, also known as IMRs. The goal of this standard is to minimize the safety risk that these robots pose to anyone working with or near the devices. This standard includes the proper procedures for risk assessments, allowing the developers and users to identify potential safety risks. This standard also specifies safety requirements to be included in the device as well as guidelines for human-robot collaboration. It also specifies guidelines on how to safely install and integrate the robot into a workplace, as well as the importance of proper training on how to use the device.

Aspects of this standard apply to the Wrench Monkey as it has the capability to be used within an industrial environment, so it would therefore have to meet the requirements of this standard to be considered safe to use.

Section 4.1.4: PCB Design Standard

ANSI/IPC-2221, titled “Generic Standard on Printed Board Design, was published originally in 2003. It was published by the Association Connecting Electronics Industries, or IPC, working with the American National Standards Institute, or ANSI. Since its publication, there have been many revisions and updates to the standard. It provides guidelines and requirements for PCB design. It covers factors such as board size and shape, component placement, electrical characteristic requirements, mechanical considerations such as tolerances, and thermal management guidelines. It also includes guidelines on its design to ensure ease of fabrication, as well as information on environmental considerations to reduce the negative environmental impact of the materials and processes required to create a PCB.

The Wrench Monkey will contain two custom PCBs, and therefore this standard will have to be considered and followed in order to meet the project requirements and create a functional product.

Section 4.1.5: LED Standard

IEC 62031:2018 was originally published by the International Electrotechnical Commission, or IEC, in 2018. This standard is titled “LED modules for general lighting - Performance requirements.” The standard specifies the performance requirements of an LED including mechanical properties, electrical characteristics, and luminous flux. It also specifies the methods and procedures to test the performance characteristics to determine if they have met the requirements, as well as many safety requirements and concerns that should be taken into consideration when designing, manufacturing, or using an LED.

The Wrench Monkey will utilize an individually addressable LED strip in order to highlight the requested tool. These standards affect the project because they ensure that the LEDs that are incorporated into the final design are safe, reliable, and of acceptable quality. This is important as it ensures the quality and functionality of the final product that is being designed.

Section 4.1.6: C Programming Language Standard

The most recent C programming standard is ISO/IEC 9899:2018, which was published in December of 2018. Starting from ANSI C89, this standard is intended to allow for the portability and compatibility of C code across different compilers and tools. The most recent version of this standard added new data types and some other functionalities.

The Wrench Monkey will utilize the C programming language as it uses the Arduino IDE. The Arduino IDE accepts the C programming language as well as the C++ programming language. Because of this, the C programming language standard is important as it has helped ensure consistency within the language itself. This helps make the coding process simpler as there are libraries that can be used within the project that are developed or downloadable in the C language to help make the code of the overall project simple and easy to understand, explain, and debug.

Section 4.1.7: Inter-Integrated Circuit (I2C)

I2C is a communication standard developed by Philips Semiconductors in 1982. This standard enables the communication between several low-speed devices that can act as masters or slaves using two wires–one of the wires being the serial data line (SDL) and the other being the serial clock line (SCL). One of the most useful properties of this standard is the ability to communicate with various devices by using the devices’ addresses while only needing two wires independent of the number of devices that are connected to the bus.

I2C is used to communicate between the ESP-32S microcontroller and the camera selected to perform the visual control of Wrench Monkey. Due to the robustness of I2C, if an additional device needs to be added to the bus, there will not be any changes to the communication between the ESP-32S and the camera.

Section 4.1.8: Portable and Rechargeable Batteries Standards

ANSI C18.2M is a standard regarding portable rechargeable cells and batteries. It was published by the National Electrical Manufacturers Association, or NEMA, and approved by the American National Standards Institute, or ANSI. There are two parts to this standard, part one covers general information and specifications, while part two covers the safety standards. Part one covers batteries based on nickel-cadmium, nickel-metal hydride, and lithium ion electrochemical systems. It assures the electrical and physical compatibility of products between different manufacturers by providing standards for aspects such as dimension, polarity, charge methods, and testing conditions. Part two specifies the performance requirements for the same type of rechargeable cells and batteries, which helps ensure the quality and safety of these products.

The Wrench Monkey is equipped with a sealed lead acid (SLA) battery, so this standard will provide assurances that the battery used is reliable, safe, and compatible with the design of the overall project.

Section 4.2: Project Constraints

A project constraint is any limitation placed on a project's design and completion that needs to be taken into consideration. Common constraints include factors such as economic, time, availability, safety, size and weight, testing, environmental, technical, and usability constraints. There are many constraints that need to be considered while completing this project. Listed below are many different constraints that have been placed on this project and how they have affected the design and completion of the final product.

Section 4.2.1: Economic Constraints

One major constraint in every project is economic constraints. Whether a project is completed for a customer or for a personal project, there is always some sort of budget that has to be adhered to. When working on a project for a company, expenses can include labor costs, material costs, the cost for the workspace, as well as aspects such as transportation costs to move or deliver the product. It is important to consider all of these things when determining the budget and the scope of a project. If a customer is requesting a product, it may require the manufacturer to do some research and sit down with the customer to discuss trade-offs they need to consider. Requesting a product with many features and functionalities would likely add to the material costs and the labor costs as it would take the manufacturer more time to complete the project. Requesting custom or high quality parts would also likely increase the material cost. It is necessary that the customer and the manufacturer are both aware of these limitations so that the budget provided is large enough to accomplish all of the requested details, as well as this provides the customer chances to potentially simplify the project for the purposes of saving money.

Another aspect of designing a project that would affect the budget is the choice of materials and the intended use of the product. While choosing the cheaper materials may seem to be the more obvious financial option, it is not always the best option. Choosing a cheaper option can potentially increase the chances of it failing and needing replacement. Replacing a cheap part multiple times may end up costing more overall than opting for a sturdier, higher quality, more expensive alternative at the start of the project. It is also important to consider the intended use of the product being designed. There are cases, such as when creating a prototype or proof of concept, that the quality and durability of a part is not as important and therefore it would be acceptable to use a cheaper alternative. However, when making a final product, choosing a higher quality part in the beginning could help decrease manufacturing costs. It could also help decrease the cost to upkeep the product once the customer is using it should the part be in a place where gradual degradation due to ample use is expected. An example of this is including higher quality tires for a vehicle working somewhere such as a construction zone. While cheaper tires may become worn down quickly in the rough terrain, using higher quality tires would require that they be replaced less often, therefore saving the customer money overall.

For the Wrench Monkey, the only costs we are taking into account are the material costs. As this project is not sponsored, the project costs are limited to what the four team members can afford to pay out of pocket. Because of this, the team has to consider the cost of parts when determining the scope of the project. It is also important to consider the different options on the market to determine how expensive the necessary components can be, and if there are cheaper alternatives available that would be high enough quality for their intended purpose in this project, to ensure that the overall project is affordable. The estimated budget for this project is around $309, and the goal is to keep it well under $1000.

Section 4.2.2: Time Constraints

Another common constraint that applies to nearly every project is time. Whether it is requested by the customer, a manager, a professor, or set by the individual, there will almost always be a deadline that things need to be done by. It is important to consider the deadline when determining the scope of a project, as well as the availability of the necessary materials. Should a project have a strict deadline, the manufacturer and the customer will have to do research and be realistic about what can be accomplished in the given time frame. When determining the expected timeframe in which to complete a project, the manufacturer will have to consider not only the time it will take to assemble the product, but also time will need to be factored in to address anything that may go wrong. This includes things like receiving faulty parts and having to reorder, long shipping times, and issues when testing the product causing a setback as the team has to determine and fix the issue. It is also important to consider the availability of necessary materials as factors such as supply chain issues, shipping times, and factors such as import and export restrictions set by governments can affect the ability to receive parts in time.

Another important thing to consider is the budget of the project and the available facilities. If the budget is higher, the manufacturer could potentially speed up the process by devoting more workers to the project. This would increase labor costs, however it may be a trade-off that the customer is willing to make. Considering the available facilities is also important as if the manufacturer is equipped with a large amount of high tech equipment that is applicable to the project, than parts of the process can be sped up by utilizing it, however if the facility is smaller and has less or slower equipment, that needs to be taken into consideration. The manufacturer can also decide that, should the budget allow it, pre-assembled parts can be ordered and incorporated, or specific aspects of the project can be outsourced. However, it may be better financially to accomplish more themselves, which would likely take longer for some components. Should it be decided that given the available budget and resources the project is unrealistic for the proposed timeline, it is necessary for the manufacturer to meet in order to either narrow down the scope of the project, or extend the allotted timeline.

In the case of this project, the deadline is a fixed date with no option to extend the timeline for any reason. Because of this, the scope of this project had to be carefully thought out and researched to determine the probability of accomplishing all the set goals. This senior design team is composed of four students. Each member of this team is currently a full time student with multiple other courses that need to be completed, as well as a few members of the team having internships in addition to classes. The team is also limited to two semesters, the spring and the summer, and the summer semester is shorter than the fall and spring semesters which decreases the amount of time to complete the project. Because of all of the above factors, the project scope was determined by carefully considering and researching how long each aspect of the project was expected to take, and then making sure that extra time was factored in for troubleshooting and fixing potential issues, as well as attempting to plan for unexpected delays so that the project could still be completed on time. Unexpected delays in the case of this project could include things such as a member of the team being unable to work on the project for a time period due to becoming sick or becoming too busy with other classes, as well as aspects such as delays in the shipping process when ordering crucial parts which could potentially put a hold on the completion of the project.

Section 4.2.3: Availability Constraints

Another constraint to be considered is availability. Project managers need to consider the availability of the items that are needed to complete a project to determine if the project is possible. For example, if the project requires a specific part in order to be successful, it has to be considered if that part is readily available at a price that will fall within budget. Due to political, environmental, and economical factors, some products may become unavailable or difficult to obtain. Should a product not be within budget or not be available in the allotted time frame, the team would have to consider raising the budget, extending the deadline, or finding an alternative part that may work as a substitute in order to complete the project.

When designing the Wrench Monkey, the team had to consider what parts would be available to obtain within the two semesters that the project would be worked on, as well as ensuring that they would arrive early enough to perform sufficient testing and account for any complications that may arise. Because of this, some products need to be ordered earlier than they are actually needed to account for any potential delays.

Section 4.2.4: Safety Constraints

One constraint that is extremely important is safety. No matter what project is being designed, safety for both the user and the team making the project have to be taken into consideration. When designing and building a project, engineers have to consider what machinery and methods would be required to create the product and they have to determine a safe way to do such tasks. They also have to incorporate safety features within the design itself to reduce the risk of injury for users.

In the case of the Wrench Monkey, a sensor is added in order to stop the toolbox and alert the users if there is an object obstructing its path. This is important as not only will it prevent possible damage to the toolbox or other items in the path, but it would also prevent injury to anyone who might be standing in or crossing through the path that the Wrench Monkey is following. Another safety constraint that is to be met is the speed. Due to the Wrench Monkey needing to operate in busy, shared workspaces while also being quite heavy, there is a maximum speed set to allow ample time to emergency stop the toolbox or step out of the way if someone or something is in its path.

Section 4.2.5: Size and Weight Constraints

When designing a project, the size and weight of the final project need to be taken into consideration. The function and location of the item need to be considered as it would determine the desired, or maximum, size and weight the product can be. For example, if the product must be carried around by the user, it should be light enough for the average person to carry, as well as small enough for them to pick up. If it is on wheels, the designer may be able to make it heavier as it would be easier to relocate. The amount of space that the product takes up is also important to consider because if the item is intended to be stored or used in a large workshop, it can be larger, however if the intended use is for it to be portable or for it to be used within a small lab than it has to be designed to be more compact.

In the case of the Wrench Monkey, as it's intended use is within a workshop it is able to be larger. However placing it on motorized wheels requires that it not be so heavy that the amount of torque within the chosen motors cannot move it from workstation to workstation.

Section 4.2.6: Testing Constraints

Another constraint to consider is the testing constraints. Project managers have to consider if they have the appropriate space and equipment to test their products throughout the design and building process. If they do not have a space equipped for what is needed, they will need to consider if the project needs to be modified, or if they need to account for additional items in their budget, such as renting or buying the required equipment or renting out a space for testing purposes.

In the case of the Wrench Monkey, the team has to be able to test each component, as well as the final project. All of this has to be able to be done with equipment at home, or available on the UCF campus. A location also has to be found on campus for a demonstration to be completed at the end of Senior Design 2.

Section 4.2.7: Environmental Constraints

When designing a project, it is important to take into account the environmental impact that the project will have. When choosing the materials and processes by which the product is to be built, there are ways to mitigate the environmental impact to be had. For example, when designing a project, it is important to consider the expected use and lifespan of not only the overall product but also the individual components. If there is a component that is expected to experience gradual deterioration due to heavy use, choosing a material that is stronger would be beneficial as it would extend the lifespan of the part and require it to be replaced less frequently. This is beneficial to the environment because it would decrease the amount of disposable waste produced from the product.

It is also important to consider the environmental impact of the individual components. For example, the Wrench Monkey is powered by a sealed lead acid (SLA) battery. A SLA battery is able to be recycled in order to ensure minimal negative environmental impacts. Unfortunately, batteries are not often disposed of correctly, leading them to leach hazardous chemicals into the nearby soil and water, which could harm people as well as ecosystems. However there are ways to properly dispose of them, which not only prevents the hazardous conditions, but it also allows for certain resources to be reused in other products, which is beneficial to the environment.

Section 4.2.8: Technical Constraints

Technical constraints are project limitations based off of the technology that is available, as well as compatibility with existing systems. When designing a project, it is important to consider current, existing technology and how it is incorporated into, or how it will interact with, the product being built. If the intent of a project is to interact with or work in conjunction with another existing piece of technology, it is important to consider how to make the two devices compatible. That will affect the technology that can be incorporated into a project, or it will require a higher budget, a longer timeline, or some other trade off in order to ensure compatibility.

It is also important to consider what existing technology can be incorporated into a project to accomplish its objectives, as well as how willing a team is to attempt to create a new technology. In the case of the Wrench Monkey, due to factors such as time constraints, it was important that the project is able to be accomplished utilizing exclusively existing technology. If a project manager should choose to create a new technology for their product, it is important for them to understand the time, funding, and research that would be required to go into it. Therefore it is more common for projects to be completed with only existing technology.

Section 4.2.9: Usability Constraints

This constraint refers to the ease of use of a product. When designing a project, it is important to consider who the target audience is and how much knowledge and training they will require to use the product. If the final product is produced with the intention of being utilized by experts in a field, designers can afford to make it more complicated as the users will understand how it works and they will likely be more willing to go through training in order to use it correctly. If the product is intended for public use, it should be assumed that the user will have very little knowledge of the product, its purpose, and its use when they attempt to use it for the first time. In this case, it is important to make the product very simple, straightforward, and easy to use with little to no training.

The Wrench Monkey is designed to be simple to use with minimal training required. Creating a user friendly interface as well as an easy set up is required to make this product easy to operate. To use the Wrench Monkey, the user will simply have to log into their work station and select the tool they need. The Wrench Monkey will then leave wherever it currently is waiting and make its way to the requested workstation. It will then illuminate the requested tool automatically. While more advanced features are available, such as the ability to preset tasks with a combination of tools, basic use of this product will require the user to have very little knowledge on how it works, and it will also require only a few buttons to be pressed before it will complete the task autonomously, making it simple to learn and utilize in a busy workspace.

Chapter 5: Comparison of Chat GPT with Other Similar Platforms

Chat GPT and other similar artificial intelligence platforms are valuable resources that can be used to aid in the completion of this project if used correctly. However, it is important to understand how these resources work and how to use them. If used correctly, these resources can be used to increase project efficiency, for example it can be used to help when researching and comparing different components. However, if used incorrectly, the use of artificial intelligence could lead to incorrect information being included or even plagiarism. Because of this, it is important to understand what options are out there and how to correctly use it as a resource without relying too heavily on it. The following section outlines different artificial intelligence options, their history, their accuracy, and the benefits and downsides of utilizing it in school, and more specifically in a senior design project.

Section 5.1: Chat GPT and Other Similar Products

Chat GPT, which stands for Generative Pre-train Transformer, is a chatbot that was first developed and launched by company OpenAI in November of 2022. The first chatbot, at the time known as a chatterbot, was developed in 1966 by Joseph Wizenbaum and called ELIZA. Since then, there have been multiple attempts to improve on the idea, such as A.L.I.C.E., Siri, and Alexa to name a few. The launch of the large language model Chat GPT introduced new features and capabilities, such as being able to learn from past interactions as well as training data, giving it the capability to constantly grow and self improve as more people interact with it. This has caused it to rapidly gain popularity as people use it to aid them in their jobs, education, as well as just holding a conversation with the chatbot to explore its capabilities.

Alternatives to Chat GPT have also since launched with similar features, such as Google Bard, Copy.ai, Hex.AI, and Microsoft Bing, which have various levels of accuracy, accessibility, and popularity. The purpose of chatbots, such as Chat GPT, is to respond to written prompts to answer questions as if the user were to be having a conversation with another person. Through machine learning, Chat GPT is able to sift through massive amounts of data and generate responses based on that data. This can be useful as it allows someone to ask a question and have it answered quickly, drawing on multiple sources to compile a comprehensive answer that otherwise could have taken the user much longer to find through traditional search means such as Google. Chat GPT also has the ability to remember what it has previously output, which allows for the user to ask follow up questions. For example, the user could ask for clarification on the previous answer and be provided with a prompt response to further explain the topic and help clear up confusion without simply restating the previous output.

Section 5.1.1: A History and Comparison of Chatbots

As previously mentioned, there have been many chatbots created since the development of ELIZA in 1966. Early chatbots such as ELIZA were created to mimic human conversation and act as a Rogerian psychotherapist, and this was accomplished by using pattern matching and substitution methodology. The chatbot would use the user input and output one of many pre-scripted responses. ELIZA lacked the ability to fully understand and generate unique responses for the user.

In 1995, A.L.I.C.E. was created. A.L.I.C.E. stands for Artificial Linguistic Internet Computer Entity, and it uses artificial intelligence markup language, or AIML. A.L.I.C.E is made to simulate the experience of talking to an actual person over the internet. Years later, in 2010, a more modern form of a chatbot was created known as Siri. Siri was marketed as an intelligent personal assistant, and was quickly followed by similar products such as Google Assistant, Cortana, and Alexa. These programs allowed for the user to ask questions and also instruct the program to complete certain tasks. The next wave of chatbots came with Chat GPT and other similar Artificial Intelligence programs.

There are now a wide range of alternatives to Chat GPT so users have many options depending on what they are hoping to get out of the product. Key factors in choosing which platform to utilize when searching for the best AI product are accessibility, accuracy, and speed. Products such as Chat GPT, Hix.ai, Chatsonic, Jasper Chat, and Copy.ai all have subscription options for the user to access higher quality, faster responses, however they also offer options that are free to access, however these free option often have less features available to use than the paid service. However, options such as Microsoft Bing, Youchat, and Perplexity AI are all free for anyone to use.

Another factor to take into consideration when choosing an AI is the functionalities offered and accuracy of the responses. For example, Perplexity AI is unable to retrieve previous responses, and it also has ethical issues as it is more prone to produce plagiarized responses than other programs. Google Bard also has issues with providing accurate and original responses as it is still in an experimental phase. Because of this users may decide to avoid using these platforms.

The program Hix.ai offers a wide range of functionalities which include the ability to analyze pdf documents, and even summarize youtube videos with only the free version of the product, which may make it a desirable alternative to Chat GPT if that is something the user is looking for. Microsoft Bing is powered by GPT-4, which could also appeal to users who want to use the functionalities of the subscription based Chat GPT option without paying a fee, however it does tend to run slower than other programs.

Most modern chatbots are equipped with the same basic features and functionalities, however there are differences between each individual platform. This allows for users to choose which option is most beneficial to them based on factors such as speed of response, accuracy of information, price of using the platform, and the functionalities it offers.

Section 5.2: Chat GPT in Education

The use of Chat GPT and other similar generative Artificial Intelligence tools within education is a topic that was widely debated, especially immediately following the 2022 Chat GPT release. Several school districts were quick to ban the use of Chat GPT on school networks. Their concern was that it would cause students to cheat on everything by just asking the chatbot to generate the answer instead of using it as a learning tool to help them understand the material. As it continues to grow, the benefits of using such a tool within education have become apparent, and educators and students alike are quickly learning to embrace it and incorporate it into the learning process.

If utilized correctly, Chat GPT could greatly enhance the learning experience through its ability to tailor to the individual to provide a personalized learning experience, as well as increase a students efficiency. However, used incorrectly, it can have the opposite effect by hindering a student's educational experience to the point where they begin to lose important skills such as critical thinking and the ability to learn independently. Because of this, many educators are hoping to incorporate chatbots into their teaching to not only aid themselves in tasks such as lesson planning, but it also provides students the opportunity to learn how to properly use these tools in a way that will benefit them without leading to an unhealthy overreliance on the tool.

Section 5.2.1: Benefits of Chat GPT in Senior Design

The use of Chat GPT in a large project, such as a Senior Design project, can greatly help the learning process if used correctly. However, it could also cause hindrances to the learning process as well as the overall project if the users are not careful. One way that the use of Chat GPT would be beneficial to use within a Senior Design project is due to its ability to quickly provide summaries and overviews of large amounts of information. For example, reading articles and research papers to find ones that are most relevant is a very time consuming process. With Chat GPT, a student could request the chatbot to summarize a paper, or to identify key information within it. This could greatly improve efficiency as the student no longer has to read and analyze papers that turn out to be irrelevant. Using Chat GPT to identify only the most relevant and helpful articles would allow the student to spend more time analyzing and understanding the content of the paper, leading to a deeper understanding of the topic. Similarly, asking Chat GPT to help analyze the datasheet of a specific device, or compare multiple datasheets, could help the team quickly and efficiently identify the optimal product to utilize in their project without the need to read through multiple data sheets.

Another benefit of the use of Chat GPT within a Senior Design project is that it can help students get a deeper understanding of different concepts, products, and devices relevant to their project. This is because of Chat GPT's ability to compile large amounts of data from a variety of sources, as well as recall past responses within a conversation to provide the ability for a user to ask follow up questions. Oftentimes during a Senior Design project, students are utilizing devices such as sensors and concepts that they have had little to no experience with. Prior to the Senior Design class, many students have little practical experience applying the concepts they have learned throughout college. Because of this, many concepts learned early on may have been forgotten, or a student may have a hard time understanding how something works practically when incorporated into a larger design. Taking the time to get a deeper understanding of how these concepts can be practically applied and how it will affect the overall project is imperative to making a design work. Chat GPT can help with this, as it may be hard to find a website or research paper that will directly answer specific questions. Public forums can be beneficial as you can ask other people with more knowledge about the topic to help you out, however this risks a person providing incorrect information, misunderstanding the question, or not answering in a timely manner and not benefitting the student. Being unable to find the answer in a timely manner can be frustrating and discouraging, however using Chat GPT can expedite this research process and help the student gain a deeper understanding of what they are trying to learn. When asking Chat GPT a question about how to use a specific motor, sensor, or how to apply a concept learned in a class, the user can be specific about what the use is and gain a more personalized response. It also allows for a quick response, and the ability for the user to have an ongoing conversation, asking for the chatbot to clarify or further elaborate on specific details. This would benefit the project as it could potentially reduce the number of failed attempts at accomplishing certain parts of the overall project.

Additionally, students can also utilize Chat GPT as a way to aid in writing the final project paper. Utilizing Chat GPT to help writing the paper can be done in one of two ways, and depending on which way it is done it can either be a beneficial tool or cause major problems. The first way is by utilizing it as a tool to check the writing that has been done, and the second way is by just asking Chat GPT to write up parts of the paper. Utilizing Chat GPT to help check over sections of the paper for grammar mistakes, formatting errors, and small inaccuracies could be very helpful in completing the project as papers of this length are inevitably going to contain some writing errors. Chat GPT could likely identify most errors that may be harder to catch, which would be beneficial as it would allow the team more time to focus on the content of the writing instead of having to worry as much about the grammar and formatting details. Chat GPT could also be used as an advanced thesaurus by asking for a way to reword a phrase or sentence to better convey an idea. This could also be beneficial as it would help the reader better understand the content of the paper.

The second method of utilizing Chat GPT for a senior design final paper is to have the AI write the paper completely. This would be detrimental as it could provide false information and Chat GPT can sometimes output responses that are easy to identify as written by artificial intelligence. It also doesn't require the person that should be writing the paper to have a full understanding of what they are writing about. This could lead to difficulties in explaining the concepts later on in the presentation, as well as difficulties in understanding how to fix any issues that may arise during the testing process. Using Chat GPT to write sections of the paper without proper citations also raises ethical concerns as it is considered plagiarism. Even though the writing may not have been taken from another piece of work directly, Artificial Intelligence options such as Chat GPT pull from information it finds online, so the user could unknowingly be using someone else's work directly. Even if it is not pulled directly from another source, Chat GPT generated papers are still not original work so it is still considered plagiarism.

Section 5.2.2: Drawbacks of Chat GPT in Senior Design

As previously stated, although Chat GPT has many benefits, if used incorrectly, it could greatly hinder the learning experience. One example of this is by a student or team blindly trusting and believing the outputs of the chatbot with no effort to verify the information. While Chat GPT can be accurate and extremely useful in expediting the research process, it also can make mistakes. The chatbot gains its information from data found on the internet, and then compiles it to create a response. However, it is not always able to distinguish between accurate and inaccurate information. If something is written and published to the internet, such as a research paper, wikipedia article, or social media post, it is incorporated into Chat GPT's training data, and Chat GPT will take that written data as fact and be unable to distinguish which piece of information is correct if it is given two conflicting statements. Because of this, when writing a response, sometimes a piece of incorrect information is utilized and can then render the entire response invalid. People who choose to utilize Chat GPT in any way need to be aware of this limitation and use their own judgment to determine if the output is reasonable. Within the scope of a project such as Senior Design, if a student or team decides to believe everything that Chat GPT says without verifying the details themselves through research and testing, it could lead them to have issues within their project that they do not know how to address as they may not fully understand what they did or the logic behind why they did it. This could not only be detrimental to the outcome of a project as it may become harder to pinpoint where the team went wrong as they may still believe that that part is correct since it was provided by the chatbot, but it also causes the students to not take the time to do any of the research and learning themselves.

Similarly, another way in which Chat GPT could hinder the learning process of students if used incorrectly is by causing them to become over reliant on it. It is important to understand how and why different things work. Senior Design provides engineering students with the unique opportunity to learn how to apply different concepts and devices that they have learned about conceptually throughout college, as well as new ones they have no prior experience with, and learn how to make them all work together to accomplish a goal. Senior Design projects help teach how to work as a team, time and project management, how to do practical research and application of devices and concepts, as well as how to identify issues and troubleshoot them to find a solution. In the end, students should have a full comprehensive experience of what it is like to work on a real life engineering project from start to finish.

Relying too heavily on Chat GPT will considerably diminish the value of the learning experience. For example, if they ask Chat GPT to give them the best product to use for a specific part of the project, they lose the opportunity to learn how to do practical research and product comparisons through datasheets, as well as learning about how to understand tradeoffs and determine which product elements are most important to them. Additionally, if they ask for it to give them detailed step-by-step instructions on how to accomplish a certain task, they lose the opportunity to use critical thinking and logic to determine how to do something. Instead of applying the knowledge they have learned and doing research to determine something, they are blindly following instructions and not making the effort to understand how and why it works.

Section 5.2.3: Conclusion

Overall, if used correctly, Chat GPT can be an amazing tool that can aid in the understanding and efficiency of a project, however if used incorrectly it can significantly hinder the student's ability to learn and gain any valuable skills and experience from the project. Students can use Chat GPT to increase efficiency in the research project by having it summarize papers to more quickly find the relevant ones, and it can also be used to compare datasheets of different product options to determine the optimal one for the team to choose for their project. Chat GPT can also be utilized to help students gain a deeper understanding of how things work and how they might apply previous knowledge practically. This can help expedite the design of the project as a deeper understanding of the individual parts and concepts and how they all interact as a whole could lead to less errors in initial testing.

Chat GPT can also be used as a writing assistant to help reword sentences and phrases to better convey an idea, or to check for grammar and formatting mistakes that may be easily overlooked. These are all ways in which Chat GPT can help students make the most out their Senior Design experience, however a student using Chat GPT to write the paper, do the research, or make decisions for them is only causing them and their team to lose understanding of the project and to lose valuable project experience that could help them in their future.

Additionally, relying on Chat GPT for everything without verifying the results could also lead to incorrect information being included or factored into the project, which could cause issues with the project's functionality and a delay in being able to complete it. So while Chat GPT and other similar artificial intelligence programs and chatbots can be an incredible tool, users need to be aware of their limitations and also be aware that over reliance on these programs is unhealthy.

Chapter 6: Hardware Design

The following chapter describes the hardware design aspects of the project. Included are descriptions of each major subsystem along with any block diagrams and schematics to help better describe the functionality of that subsystem. The main components are the boards related to the tool detection, power distribution, motor control, ultrasonic collision avoidance, line detection, and the main control board which incorporates most of these subsystems.

Section 6.1: Tool Detection

The Wrench Monkey project employs a dual approach to discerning the presence of tools within its drawers, combining the functionality of thin film pressure sensors and RFID technology. Thin film pressure sensors serve as the first method in detecting the presence of tools within the drawers. These sensors, akin to miniature detectors, are strategically placed within the drawers to register changes in pressure when a tool is placed upon them. This intuitive mechanism allows the system to quickly identify the presence of a tool and initiate the necessary actions accordingly.

In parallel, RFID technology adds another method of tool detection. A few tools are equipped with an RFID sticker containing a unique identifier chip that emits distinct signals. These signals are then captured by RFID readers discreetly installed within the drawers. By leveraging RFID technology, the system can precisely identify the presence of specific tools and track their movements with pinpoint accuracy. The integration of these two detection methods is illustrated in the provided block diagram, showcasing the seamless interaction between the various components. Signals from the RFID stickers and data from the pressure sensors are collected and relayed to the central ESP32 microcontroller, which serves as the neural hub of the system. Here, the microcontroller processes the incoming data, analyzing it to determine the status of each drawer and its contents.

Upon processing the information, the microcontroller issues instructions to the LED strip, triggering a visual response that indicates the presence or absence of tools within the drawers. This visual feedback mechanism allows users to easily ascertain the status of each drawer at a glance, facilitating efficient tool retrieval and enhancing overall workflow productivity.In essence, the combination of thin film pressure sensors and RFID technology, orchestrated by the ESP32 microcontroller, culminates in a sophisticated tool detection system that streamlines operations and maximizes efficiency in industrial environments. By providing real-time visibility into drawer contents through intuitive visual indicators, the Wrench Monkey project sets a new standard for tool management and organization in the workplace.

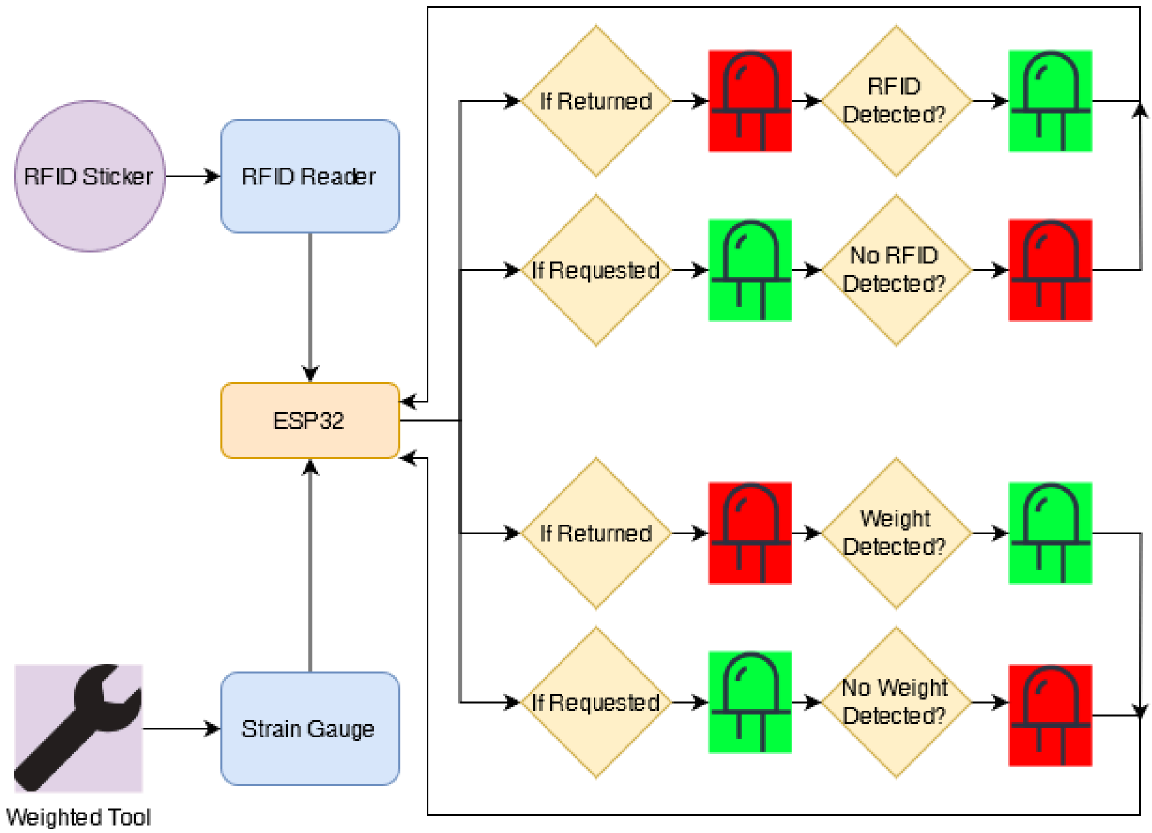

Image 6.1: Tool Detection Block Diagram

Section 6.1.1: Pressure Sensors

In this project, thin film pressure sensors serve as a key method for detecting tools within the drawer. To implement this, each pressure sensor is connected to the ESP32 microcontroller in a specific configuration. One side of the pressure sensor is linked to the 3.3 volt pin on the ESP32, while the other side is connected to the ground pin through a one kilo ohm resistor. Additionally, the same side of the pressure sensor is also linked to a GPIO pin on the ESP32. This setup is replicated for a second pressure sensor to cover the entire drawer area effectively.

Furthermore, the individually addressable LED strip, crucial for illuminating the requested tool, is integrated into the system. This LED strip, utilizing WS2812B technology, is connected by wiring it to the ESP32 microcontroller. The ground wire is connected to the ground pin, the Vcc wire to the 3.3V pin, and the data in wire to a GPIO pin via a 330 ohm resistor to transmit the data.

Once the wiring is complete, attention turns to crafting the tray insert. This involves procuring two pieces of black craft foam, each measuring 12” by 18”. On one sheet, the outlines of the tools intended for the drawer are traced and cut out using an Exacto knife. The pressure sensors are then positioned within the holes corresponding to each tool's location, and the two foam pieces are securely attached together. Subsequently, the LED strip is placed beneath where the tool is placed within the foam cutout, and labels are affixed atop each tool. These labels are crafted using a 3D printed tool name made from clear PLA, ensuring that the LEDs can effectively illuminate the name of each requested tool and be visible to the user.

Section 6.1.2: RFID

The second approach for tool detection in this project involves the use of RFID stickers. This method entails programming and reading the RFID stickers with the aid of an RFID module and the ESP32 microcontroller. To set this up, the MFRC522 two-way radio transmitter-receiver, serving as the RFID module, is connected to the ESP32. This connection is established by wiring specific pins of the MFRC522 module to GPIO pins on the ESP32. For instance, the reset pin (RST) and the slave select pin (SS or SDA) are linked to GPIO pins for communication. Additionally, the serial clock pin (SCK) is connected to pin 18, while the MISO and MOSI pins are connected to pins 23 and 19, respectively. The power supply connections are made by connecting the Vcc pin of the MFRC522 module to the 3.3V pin of the ESP32, and the ground pin to the ground pin.

Following the setup of the RFID module, the RFID stickers are affixed to the respective tools. Subsequently, the RFID reader, comprising the MFRC522 module, is strategically placed between the layers of foam forming the tray insert, beneath the designated location for each tool. This positioning ensures that the RFID reader can effectively detect the RFID stickers when the tools are placed back into the drawer. When a tool is returned to its designated spot, the RFID reader reads the corresponding sticker and transmits a signal to indicate the presence of the tool in the drawer. This seamless integration of RFID technology enhances the accuracy and efficiency of tool detection within the system. A picture of the foam insert is shown below, containing the tools and sensors that are to be incorporated.

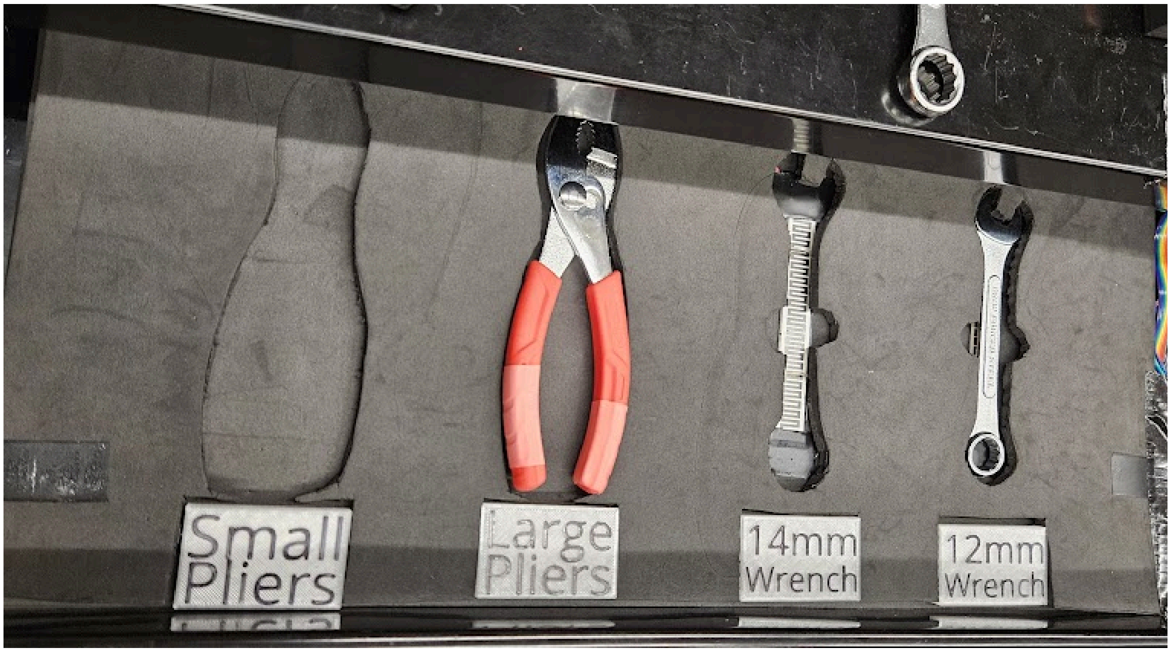

Image 6.2: Toolbox Tray Insert

Section 6.2: Power Distribution

In our project, establishing a versatile power supply setup was paramount to ensure the seamless operation of various components, necessitating three distinct voltage rails: 12V, 5V, and 3.3V. While the 12V rail efficiently powers our motors directly from the battery with minimal regulation, providing power to peripherals such as sensors and the MCU at 5V and 3.3V presented a formidable challenge. The substantial voltage disparity from the battery rendered traditional linear regulators impractical, as they would incur excessive heat dissipation, particularly under even modest loads.

To avoid this, we strategically opted for integrated DC-DC switching regulators. These compact yet highly efficient devices offer a superior solution for converting battery voltage to the requisite levels without succumbing to the heat-related limitations of linear regulators. The selected packages boast a small footprint, capable of accommodating up to 1 amp of current without necessitating cumbersome heat sinks, even under conditions of maximum power delivery. Moreover, the all-inclusive nature of these regulators obviates the need for external components, as all essential switching circuitry is encapsulated within the package itself. To further enhance performance, bypass capacitors are judiciously employed at both the input and output stages to mitigate switching noise, ensuring stable and reliable power distribution to our peripherals and MCU.

The integration of the power board directly to the battery terminals represents a strategic design choice, obviating the need for intricate circuitry to regulate power discharge. In this regard, inherent protection mechanisms built into the battery itself serve as safeguarding measures, negating the necessity for additional circuitry and streamlining the overall integration process. By simplifying the interface between the battery and power board, we can allocate resources more efficiently, directing our efforts towards optimizing other critical subsystems within the project.

Overall, the implementation of integrated DC-DC switching regulators and the direct connection of the power board to the battery terminals exemplify our commitment to innovation and efficiency in power management. By circumventing the limitations of traditional linear regulators and leveraging compact, efficient solutions, we ensure robust and reliable power distribution throughout our system, laying the foundation for seamless functionality and performance excellence.

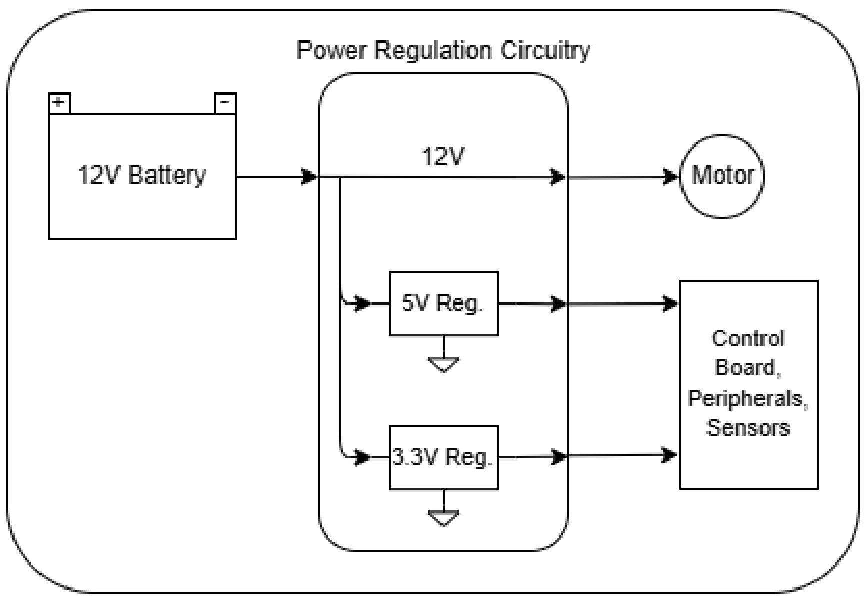

Image 6.3: Power Distribution Board Block Diagram

Section 6.3: Motor Control System

The Wrench Monkey project, with its focus on accurate line following for navigation, necessitates a significant allocation of its hardware resources to the components of the motor controls system. This is a crucial aspect of the project. For instance, our control system hardware will need specific sensors. These could be either five Infrared (IR) sensors or a combination of a color sensor and an RFID reader. The choice will depend on whether the IR sensors are selected for the final design.

In addition to these sensors, there are other components involved. These include passive devices and the ESP32. The ESP32 is a key component of the system, providing the necessary processing power to properly move Wrench Monkey where it needs to go. Another important component in the design is an H-bridge Integrated Circuit. This IC plays a vital role in enabling the switching of motor voltage polarity in a solid-state form factor, manipulable with MCU logic level voltages. The specific H-bridge used for the Wrench Monkey project is the L298H. The L298H was chosen for its ability to control two motors simultaneously, a feature that allows the motorized chassis to be easily controlled with minimal IO pin usage.

Additionally, it is also capable of supporting Pulse Width Modulation (PWM) signals. This is achieved through the use of the enable pins. Importantly, the L298 can handle these signals without causing damage to the controller or leading to excessive heat dissipation. This makes it a reliable and safe choice for the project. In summary, the Wrench Monkey project employs a range of hardware components, each playing a critical role in the system’s operation. The careful selection and integration of these components ensures proper operation of the system.

Section 6.4: Ultrasonic Collision Avoidance

In the Wrench Monkey project, the HC-SR04 ultrasonic distance sensor is being used in implementing the rudimentary object collision avoidance. Positioned in the front of the toolbox, this sensor will provide sufficient coverage, ensuring that the robot can detect obstacles in the path of movement. This easily allows obstacle detection, whether the object is stationary or a moving entity, such as a person.

Utilizing ultrasonic sound waves, the HC-SR04 sensor measures the distance to objects in its vicinity with sufficient accuracy. When an obstacle is detected within its detection range, the information is sent from the sensor to the main control board. Upon receiving the obstacle detection signal, the robot stops moving and alerts the user that an obstacle has been detected. Until the obstacle is removed, the Wrench Monkey will stay in place.

An advantage of the HC-SR04 sensor is its self-contained nature, requiring minimal additional circuitry for operation. Powered by the 5V rail provided by the main control board’s power circuitry, the sensor functions as a standalone module, simplifying integration into the Wrench Monkey system. With straightforward connections to the main control board, the sensor seamlessly interfaces with the system as a whole.

In essence, the HC-SR04 ultrasonic distance sensor serves as a crucial component in the Wrench Monkey project's collision avoidance mechanism. By leveraging its precise detection capabilities and deploying multiple sensors to eliminate blind spots, the system ensures the robot can navigate its environment safely and effectively. Through seamless integration with the main control board and minimal additional circuitry requirements, the sensor contributes to a streamlined and robust collision avoidance solution, enhancing the project's safety in use.

Section 6.5: Line Detection

In our project, the implementation of line detection hardware utilizing an array of infrared (IR) sensors serves as an essential component in enabling the Wrench Monkey to navigate its environment with precision and accuracy. While traditional line-following algorithms often rely on a single sensor to detect the presence of a line, we have opted for a more sophisticated approach by incorporating multiple IR sensors into our design. This decision is rooted in the recognition that while a single sensor can facilitate basic line-following behavior, it often results in erratic movement and limited control over the robot's trajectory.

By leveraging an array of IR sensors, we are able to achieve a higher degree of fidelity in detecting and tracking lines within the robot's operating environment. Each sensor contributes unique data points, allowing for a more comprehensive understanding of the surrounding lines (i.e. curves or other breaks in the line) and thus enable the robot to make informed navigation decisions in real-time. This distributed sensing approach not only enhances the reliability and robustness of the line detection system but also opens the door to more sophisticated control schemes that can adapt to a variety of environmental conditions and challenges.

One of the key advantages of employing multiple sensors is the ability to implement more complex control algorithms that take into account the relative positions and readings of each sensor. By analyzing the data from multiple sensors simultaneously, the robot can dynamically adjust its speed, direction, and motor speed angle to maintain optimal alignment with the detected line. This level of control granularity ensures smoother and more consistent movement, reducing the likelihood of overshooting or veering off course.

In terms of hardware implementation, the board to which these IR sensors are connected is designed to be straightforward yet highly effective. Each sensor is interfaced with an amplifier circuit, which amplifies the signal output from the sensor to provide a more reliable indication of whether the sensor is detecting a black line. This amplified signal is then fed into the robot's control system, where it is processed and utilized to inform navigation decisions in real-time. By simplifying the hardware architecture while maintaining robust signal processing capabilities, we ensure that our line detection system is not only effective but also scalable and easy to integrate into existing robotic platforms.

Section 6.6: Custom PCB

The custom PCB interfaces with all of the peripherals and acts as a gateway for controlling all aspects of the system. The main control board of the Wrench Monkey project serves as the central hub for the subsystems and the various critical components. At its core, the ESP32 microcontroller interfaces with these peripherals and allows communication between them. With the abundance of GPIO pins and native support for various communication protocols, the ESP32 easily interfaces with the ultrasonic sensors for obstacle detection, RFID sensors for tool identification, resistive strain gauges for precise tool detection, LEDs for tool illumination, IR sensors for line detection, and the H-bridge for motor control. Additionally, encoder feedback from the motors provides crucial data for precise motor control and feedback mechanisms.

The ESP32's integrated WiFi capability further amplifies its utility by enabling users to interact with the system remotely. This wireless connectivity empowers users to monitor the project's status, adjust parameters, and receive real-time feedback, enhancing the project's accessibility and user experience. In the design and layout of the main control board, attention is paid to various considerations to ensure optimal performance and reliability. Decoupling capacitors are strategically placed to mitigate noise and stabilize voltage levels, thus safeguarding sensitive components from electrical disturbances. Moreover, careful routing of PCB traces is implemented to minimize interference and ensure reliable data transfer between components, free of unwanted noise.

A particularly critical aspect of the board's design involves the placement of the ESP32's integrated antenna. Positioned at the edge of the board, this placement allows the antenna to operate effectively without being obstructed by other components or copper planes, thus optimizing WiFi performance and signal strength. This careful placement ensures reliable wireless connectivity and preserves the system's overall integrity.

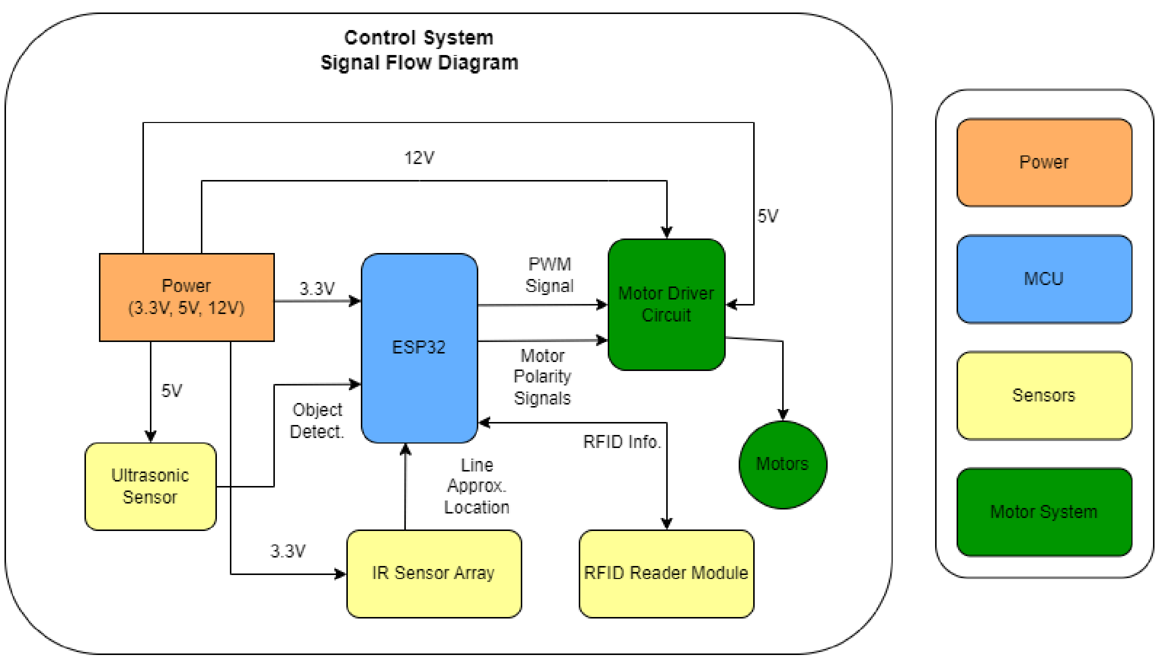

Image 6.4: Control System Signal Flow Diagram

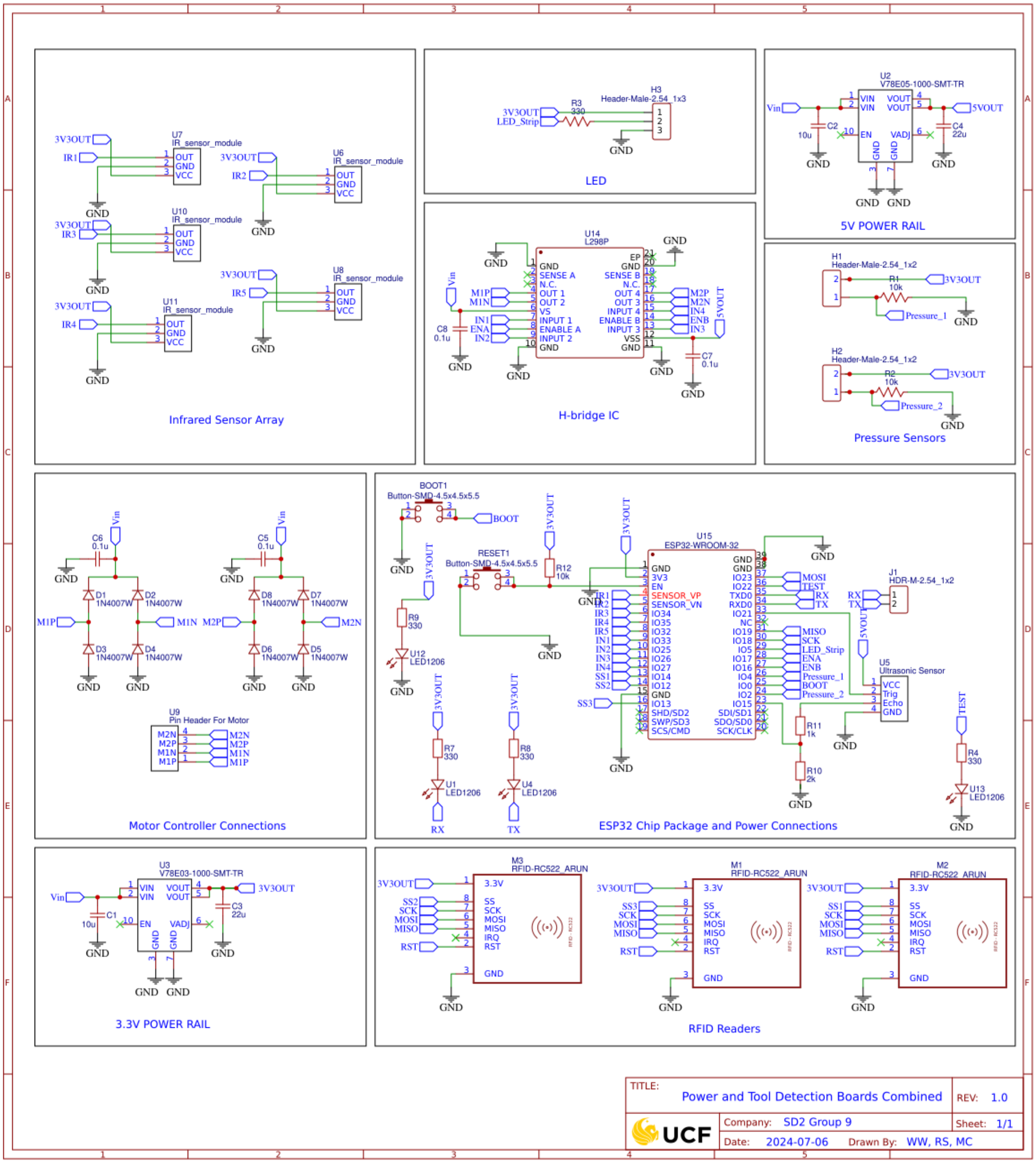

Image 6.5: PCB Schematic

Chapter 7: Software Development

The software portion of the Wrench Monkey project uses a diverse set of programming languages to address various components. JavaScript and HTML serve as the foundation for designing and deploying the website as part of the MERN stack. On the other hand, for the ESP32 module's programming, we used Arduino's programming language, rooted in C++. The integration of these languages allow for communication between hardware and software elements, making it possible to control the Wrench Monkey robot from any device.

Section 7.1: MERN Stack Development

The selection of the MERN stack, which is composed of MongoDB, Express.js, React.js, and Node.js, for full stack development has numerous advantages. As mentioned previously in section 3.2, this full stack offers many benefits for the Wrench Monkey project for both web and mobile app development. MongoDB is chosen for its scalability, flexibility, and compatibility with the dynamic data requirements. Express.js and Node.js handle server-side logic efficiently, allowing for communications between frontend and backend components. On the other hand, React.js powers the frontend with its component-based architecture, giving the ability to facilitate a responsive user interface.

One of the primary reasons for selecting the MERN stack is its code reusability between both web and mobile app platforms. By using JavaScript syntax throughout the stack, it's easy for multiple pages to share the same code components, APIs, and logic, reducing development time. Additionally, MERN stack has an extensive ecosystem including a large collection of libraries, tools, and community support allowing for a streamlined development process.

Section 7.1.1: Database Contents

MongoDB serves as the backbone of the Wrench Monkey project's database, facilitating storage and management of critical data for both the website and mobile application components. The database contents encompass a wide range of information essential to the project's functionality. There are two options for hosting our database: Hosting it locally with port forwarding or hosting it online using MongoDB Atlas. For this project we chose the easy free option, MongoDB Atlas. I want to mention that each item in the database is given a unique id number that we can use to interface with it. This makes using this database easier than others because we don't have to search for a specific string to edit.

Even though for this project there is only one robot to interface with, it was decided to make a robot number, which represents the name of each database, allowing for future expansion and creation of tool chests. As the project grows beyond senior design, one or two additional robots can be seamlessly integrated into the system, each with its dedicated database for managing user profiles, tool information, and transaction histories.

Firstly, MongoDB stores user profiles, including the user's full name, email, and password. Additionally, the user enters a robot number during registration determining which database to store the user's information in. If the robot number entered has not been previously used, it changes the database number, subsequently creating all the required collections (or sub-databases) such as Tools, History, Status, and Users. The user's information is stored in the Users collection. The first user added to each database automatically is given administrator status, with every user after getting a user status. The password for the user is then hashed with md5 encryption to ensure secure data handling and protect the user's credentials from unauthorized access or breaches.

Beyond handling each user's information, MongoDB is also used to store tool information. The information included with each new tool includes the tool name, availability status, RFID number, and tool slot number. This data enables efficient tool management and tracking within the Wrench Monkey ecosystem. The availability status indicates whether a tool is currently in use or available for checkout which is changed often throughout the use of the robot, facilitating real-time inventory management.

Like the tool collection, user's have the option to make jobs, thus we need a Jobs collection. The jobs collection includes details such as a name and an array of tools needed for a specific job. The functionality of the job is to present the tools that are needed for the job and check them out one at a time in a similar manner as the tool handler. Instead of making arrays of all details of each tool needed, it is easier to make an array of the tool's database ID or unique ID as mentioned previously. This makes it easier to add and remove tools from specific jobs should they be deemed not necessary by the administrator.

Next, MongoDB is used to capture the history of tool check-outs and check-ins. This maintains a log of transactions that includes two timestamps, user IDs, and tool IDs. The user ID and tool ID is used to pull information from the database more smoothly. Each entry also includes a Check-Out time and a Check-In time. If the user recently checked out a tool, the check in time remains as "N/A" until the tool is replaced, or the status of the tool is 1. This data provides insights into tool usage patterns, maintenance needs, and user behavior. It also holds those who have misplaced or forgot to check in a tool responsible for their actions.

Finally, there is a collection that stores data about the robot's overall status. The first two entries of this collection show information about whether or not the robot is currently connected to the backend framework along with the last time and date the previous information was checked. Next, there is a field that stores the robot's current station (its location along the line). If the emergency stop button was pushed, then the current station is listed as "Unknown" until it updates this field again. The last two fields in the status collection are a traveling boolean and a destination station string. The traveling boolean is in place to let all users know that the robot is currently in motion. If the traveling boolean is set to true there must also be a destination station used to tell the robot which RFID tag to look for. This completes the structure for each robot's database.

MongoDB's document-oriented structure and flexible querying capabilities make it an ideal choice for managing the diverse data types mentioned above. This supports the evolving needs of the Wrench Monkey project. A visual representation of the MongoDB database structure for a default robot number is shown in image 7.1 below.

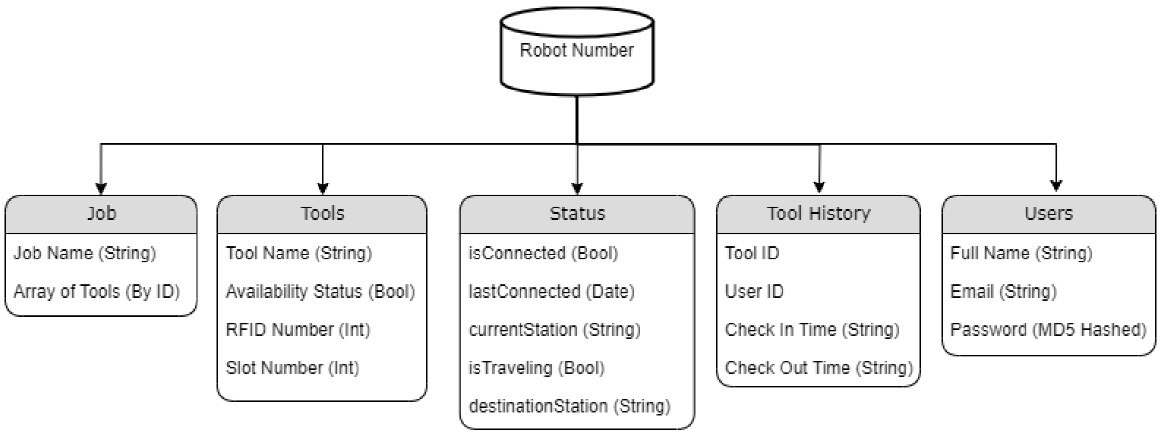

Image 7.1: MongoDB data structure diagram

Section 7.1.2: Desktop Website Development

When developing the desktop website for the Wrench Monkey project, I chose Visual Studio Code as my primary code editor, utilizing the plugins available to make coding JavaScript of the MERN stack easier. Before delving into the code implementation, I took a step back and initiated the development process by creating prototypes in Figma. Figma is an easier way, than traditional methods like photoshop, to create, test, and share designs for desktop and mobile applications. Once developing potential designs, it was easy to share the proposal with the rest of the team and gauge their input. An example of the register, login, and manager screen prototype created in Figma is shown in image 7.2 below.

After coming up with the design for each page it was time to implement it using the React framework. I would like to note that the tailwinds plugin for react was implemented to provide smooth css editing. Tailwinds allows developers to directly modify the style sheets within the JavaScript file for each tag or item, without creating a separate CSS file. Though some developers find making a separate CSS file easier and cleaner for code viewing, I find that using tailwinds makes coding stylesheets simpler and easy to pinpoint problems.

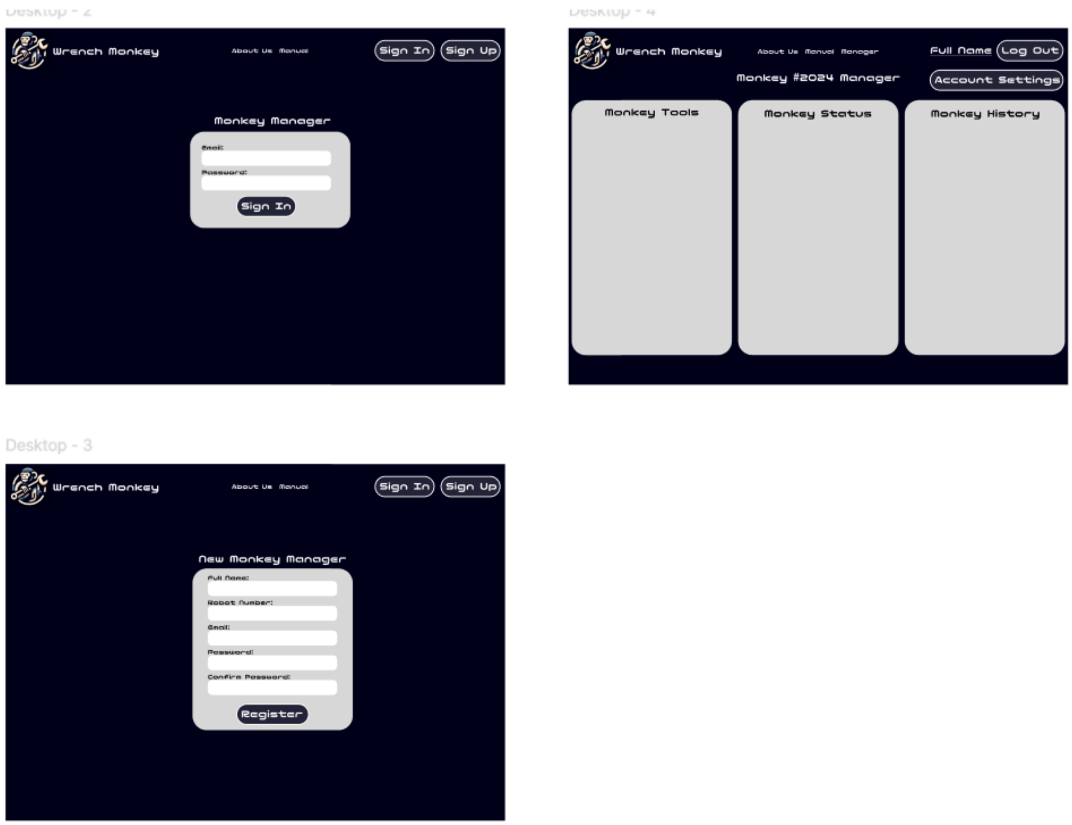

Image 7.2: Figma Prototype of Register, Login, and Manager Page

The modular structure of React components allowed for efficient development of the website. I first started out by adding a home page and developing two components. The two components "Button" and "Navbar" consisted of items that would be displayed on almost all pages. I stuck with the original prototyped design and made the buttons round in shape, while looking futuristic. I then moved on to creating the navbar, which is displayed on all pages, with modifications being made when actually logged in like showing the user's full name, the manager page button, and a logout button. I also wanted to make sure that when a user is logged in, they no longer have access to the login and register pages. Once the two main components were completed, I created an about, manual, login, register, and manager page incorporating the newly created navigation bar.

Starting off with the home page, I made a simple title and a brief description listing the reasons why we decided to go with this project. I also added a picture showing the final look of the Wrench Monkey robot. Below that, I added a section where the user can download the installation file for the Wrench Monkey Android application. The download button gives the user a warning that since the app is not on the official google play store, users may choose to scan the app but must enable unknown sources in the developer options of their phone. At this point there is no plan on creating an iPhone app, but throughout testing the expo app works perfectly fine on both Android and IOS. The reason for not creating an

IOS app is the long approval process and the minimum of 100 USD our team would have to put up front. Below the mobile application section, I decided to list both the desktop website and mobile application github links making our project fully open source to anyone.

Next, I added the about page which gives a picture of each member in this project along with our current major, a list of tasks for this project, and a quick description of our interests along with future plans after graduation. After that, a manual page was added for those who need help setting up the robot. This page is recommended for all users who are coming across the Wrench Monkey application. The manual explains in detail about setting up an account, using an administrator account, using a user account, and setting up the line following track for the robot. Each section includes screenshots and brief descriptions explaining what the user can do with a certain action like the user page which shows checking in and out tools and jobs, moving the robot, and viewing the history of check-outs and check-ins.

After that, I set up the registration page which allows a user to sign up for an account using their full name, robot number, email, and password. The website automatically checks to make sure that the robot number contains only numbers, the email is a valid email address, the email has not been previously used, and the password is secure containing at least eight characters. This page alerts the user if any of these conditions are not met by providing a red outline around the text box in question and a message below telling the user what is missing. By highlighting the errors, we are accessible for users with disabilities such as color blindness or other vision impairments. Once all conditions are met, the data is sent to the MongoDB database as shown in the image in section 7.1.1. Though our stretch goal was not met, given time constraints, I had hoped to implement an email verification system, which makes the user click on a link in their email inbox to verify the email is real.

Once the user has successfully created an account, the user goes to the login page and uses the email and password they just created to log into their own Monkey Manager. The website makes sure that the email is a valid email address and the password is at least eight characters long. If for whatever reason the email and password combination is not stored in the database, the website flags the login as invalid and notify the user that the email/password combination is incorrect. Once the user is logged into their account, the navigation bar changes slightly with the removal of the “Sign In” and “Sign Up” buttons and is replaced with a welcome message containing the user’s full name, a button for logging out, and a button for accessing their private Monkey Manager page.

The Monkey Manager page consists of all the controls required to use the Wrench Monkey along with bonus user controls. Each user is a page containing three main columns containing tool and job information, the current Wrench

Monkey status, and the tool history. The tool information, job information, and the tool history are automatically fetched from the MongoDB database. There is also an option to search the tool history, which fetches the latest tool or user in question from the database. By default, the history section is sorted by most recent action whether that be a user checking in or checking out a tool. In the tool section, if the person logged in is an administrator, there are options to add a tool, edit a tool, or remove a tool along with adding a job, editing a job, or removing a job, which automatically updates the database. If the user logged in is a regular user, they have the option to check out a tool, if available, or check out a job, so long as all tools in the job are available. All tasks involving checking in or out tools and jobs require that the robot is connected, via its websocket, to the backend server. If there is no connection, or the robot loses connection, an error message is displayed, and the user will not be allowed to continue.

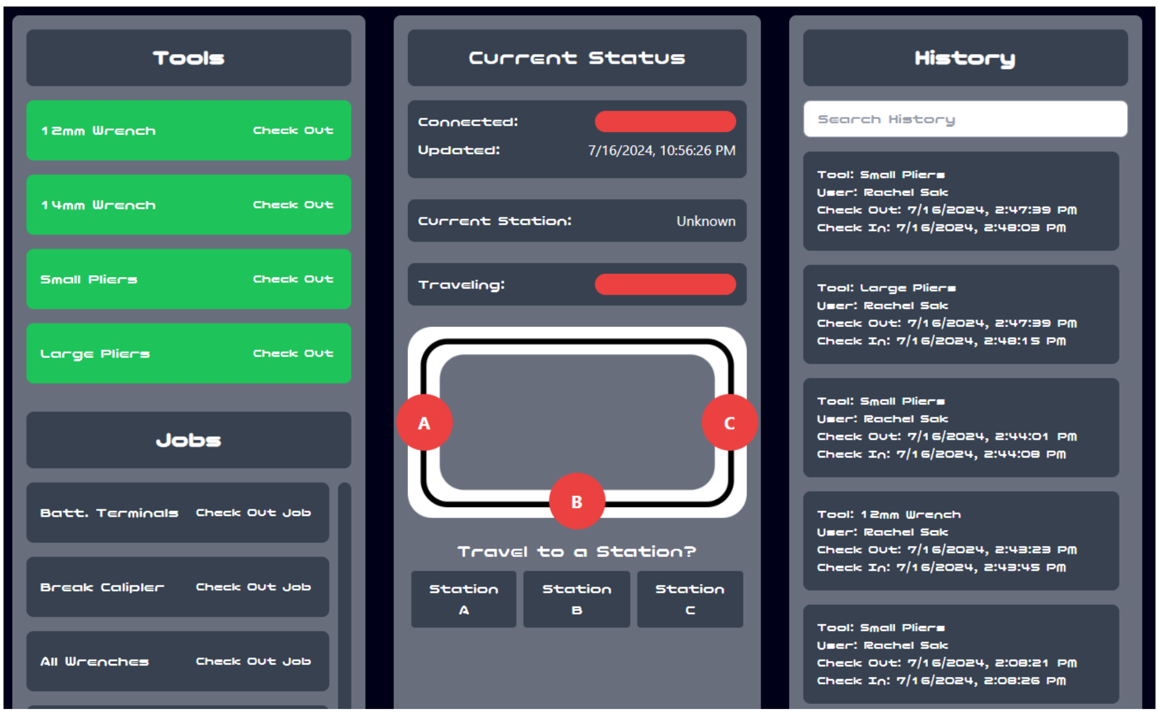

Image 7.3: User Dashboard Screen

Finally, the Monkey "current status" column in the middle of the screen as shown in Image 7.3 shows the status of the Wrench Monkey robot. If the robot is connected it lets the user know and the time associated with the check. If the robot is stationary it tells the user which station the robot is currently at and gives options to travel to the other available stations. If the robot is currently traveling from one station to another, the website lets the user know which station the robot is traveling to and gives an option to emergency stop the robot. This button is primarily used if the robot veers off the lined track or if an object not picked up by the ultrasonic sensor is about to be run over. A simple use case diagram is shown in Image 7.4, explaining exactly who can access which parts of the website at a certain time and which actions are communicated directly with the server. The three users used in the diagram are the Guest, Registered User, and Administrator. You can see that the administrator and user share almost all of the same resources except for the ability to modify tools and jobs.

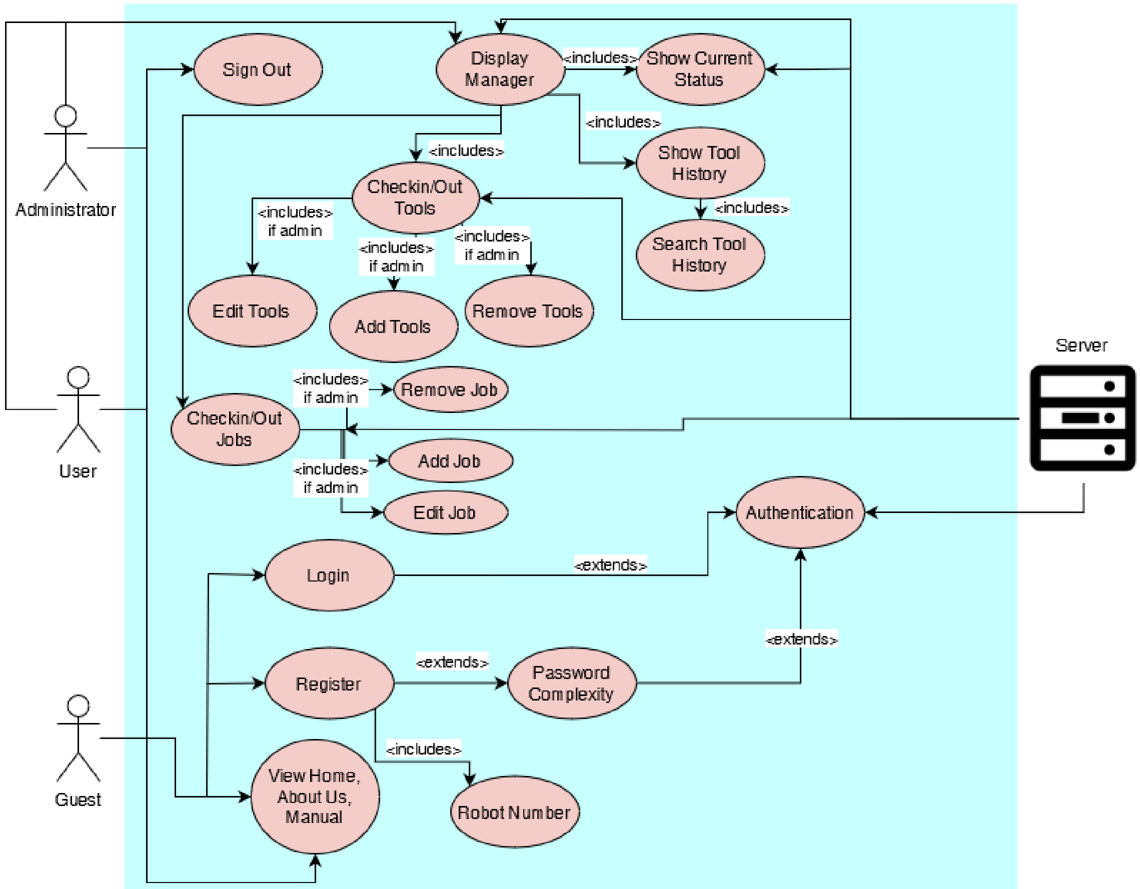

Image 7.4: Website Use Case Diagram

To ensure a seamless and real-time user experience, I implemented a stream setup using Server-Sent Events (SSE). This allows the website to automatically update settings and data without requiring a page refresh. The backend server is configured to push updates to the client whenever there are changes in the database or robot status. On the client side, the EventSource API listens for these updates and dynamically updates the DOM, ensuring that users always have the most current information. This setup also includes robust error handling to manage connection drops or update failures, automatically attempting to reconnect and resume updates. This real-time update system enhances efficiency and responsiveness for all users, whether they are administrators or regular users.

Because of this configuration, user’s and administrators can talk, and get updates from the Wrench Monkey robot from anywhere in the world and not just when standing in the same room. Though some lines are overlapping, I believe it is easy enough to see that the user and administrator has access to the home page, about us, and manual just like a guest user but that is the only similarity between the three. The desktop website development phase has laid a solid foundation for the Wrench Monkey project in whole and the development of the mobile application.

Section 7.1.3: Mobile Application Development

For the mobile application development of the Wrench Monkey project, the primary focus has been on Android app development, with future plans to create an iOS application, utilizing the same MERN stack as the desktop website. I again chose my primary editor as VS Code utilizing the Expo Go application on my personal Samsung S8 device for testing. Though I used this device for testing, and the current Android version is 9, I have personally installed the application on multiple newer Android devices and ensured they work similarly. This approach ensures consistency across platforms and leverages the advantages of the components making up the MERN stack for efficient backend and frontend development.

The Expo platform, coupled with React Native, provides a method for rapid prototyping and development of cross-platform mobile applications. The Expo Go application for Android was a huge help throughout development of the mobile applications. It allowed for instant testing and debugging, providing real-time feedback on app behavior and performance. This is easily achieved by hosting a temporary web server on my computer, no different from the web server used for website development, allowing you to run the Expo Go app on your mobile device and connect to your live coding session. Every edit made in VS code automatically updated the display and functionality of the app.

As per the desktop website, the first step of development was making Figma Prototypes for all pages of the app. The app is supposed to be more condensed than the desktop interface, so it is meant to lack accessibility to pages such as the about us, manual, or home pages without logging in. Since the screen size for a mobile phone is many times smaller than its desktop counterpart, fitting all the essential functions was more challenging but crucial for a user-friendly experience.

The mobile app starts off by showing a loading screen. This is a key feature for mobile app development, improving user experience, as not all phones are built the same nor are all network conditions. The loading screen appears during the login process or when fetching data from the database, ensuring smooth app functionality. Other than the loading screen, the mobile app interface is streamlined to focus on essential functionalities accessible through the login page, register page, and manager page.

After the app has first loaded in, the user will be brought to a new user screen where there is a brief description of what the app is used for and an option for new users to create an account, or for users who made an account on the website to log in. If this is the first time the user is interacting with Wrench Monkey's processes, they are redirected to the register page where they enter the same information shown on the desktop website. The registration page consists of boxes for the users full name, robot number, email, and password to create an account. Users will get the same treatment making an account on both devices, as input boxes are given a red border if an error is to happen such as incorrect email format or a password with less than eight characters. It is okay if the robot number is used multiple times as there can be any number of users accessing one robot's contents. Once registration is complete and the content is authenticized, the app uses a modal to tell the user the account was successfully created and redirect the user to the login page to enter their account details.

Once the user is logged in for the first time, the app will automatically remember their login information such that they do not need to log in every time the app is started up. The manager page is very different from the desktop website as all details are condensed on a smaller screen. Nevertheless, the overall content remains the same. In the navigation bar at the top of the screen, as shown in Image 7.5 below, the signed in user will see their full name along with the Wrench Monkey logo. If the user clicks on their name/profile, they are brought to a new screen that allows them to log out and delete their locally saved information. I do want to note, this does not delete their account, but instead removes the auto log in capability previously mentioned.

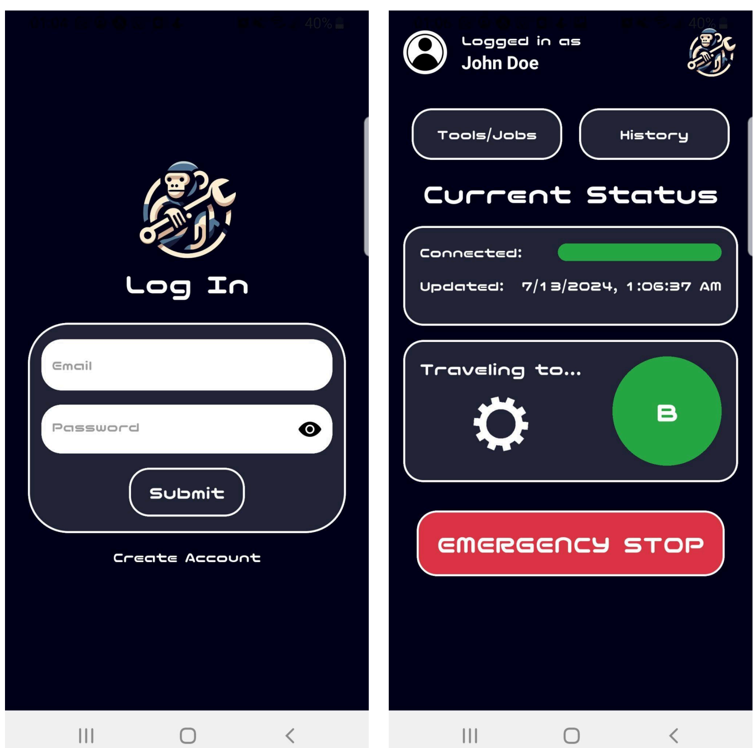

Image 7.5: Mobile Application Login and Home Page (robot is traveling)

When looking at the actual content of the manager page, instead of three distinct boxes holding the tool and job information, tool history, and the current wrench monkey status like the desktop website shows, we are instead given the status outright along with buttons to access the tool and history pages respectively. When clicking on the *Tools* page, tool information is automatically pulled from the database populating the list. On the right next to each tool there is an option to check out or check in a specific tool indicated by the red or green status of the tool. Below that is a scrollable window containing the available jobs. Like the website, clicking on a job tells the user the tools required for the job but will not let the user check out the job if all the tools are not present. Returning to the manager page, the other button that was added is labeled as History. When clicking on the History button the user is brought to a new page which is populated from the database immediately. This page shows the entire history of tool check-ins and check-outs with the tool and user information. The main option a user has in this window is to search a string, which searches by tool name or user who used the tool. The user then can scroll through the list of entries organized by most recently modified or added.

Finally, back on the main manager page, the user has the ability to see the live status of the Wrench Monkey robot. As with the desktop website, if the Monkey is currently stationary, it tells the user which station it's currently at. Respectively, if the Monkey is currently traveling, it shows the user which station the monkey is traveling to. The user also has the ability to emergency stop the robot at any point along its travel for any reason with the touch of a button. Image 7.6, shown below, shows the class diagram of the mobile application and how data is sent and received between every major software component.

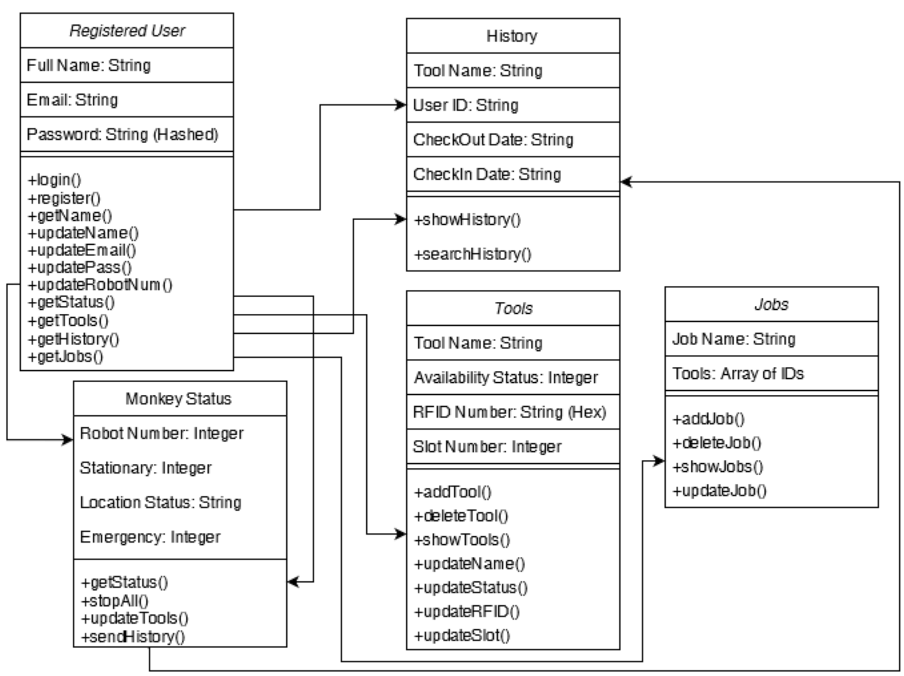

Image 7.6: Class Diagram of Mobile Application

If more time was permitted, I would create a duplicate of this application for iOS use and also host both the iOS and Android application on their respective app stores. The overall goal is to maintain feature parity and consistency across all devices, Android, iOS and Desktop browsing, delivering a seamless experience regardless of the user's device preference.

Section 7.1.4: Hosting

For the hosting infrastructure of the Wrench Monkey project, a combination of MonogDB's Atlas cloud, GoDaddy, and Amazon Web Services (AWS) have been used. Firstly, GoDaddy is utilized for domain name registration and management. This ensures that the project has a unique and easily identifiable web address, making it accessible to users across the internet. When first starting this project, we initially decided that registering for a domain name was not in our interest. This is primarily because we did not want to be bogged down with extra costs to run the entire project, especially costs with a monthly fee. Once we had looked into some domain name services such as GoDaddy and found that the price is usually a small yearly fee, especially for sites ending with untraditional domain extensions like .us or .pro. Given the price point was set around $0.99 USD per year, the domain name can reflect the project's focus and target audience while maintaining our set budget. We have selected "wrenchmonkey.life" for this reason, coming in at about $1.99 per year.

On the other hand, MongoDB Atlas is used for database hosting and management. As we have seen earlier in this project, we are using MongoDB to store our website's database features such as tool information, history of tools used, and user information. MongoDB Atlas seamlessly integrates with our MongoDB database, providing a cloud-based solution that ensures data reliability and accessibility. Though MonogDB's Atlas has many amazing features such as its automated backups, advanced security through IP whitelisting, and its scalable architecture, they won't be utilized to its fullest extent in the Wrench Monkey project. The main benefit of using atlas for our project is its low-latency data access. Prior to choosing Atlas, we were contemplating choosing MySQL as our main database host. The downside of using MySQL would be the latency between fetching and posting data to and from the database.

AWS played a critical role in our project's success. We used two instances (or shell consoles) to host the frontend and backend. Communicating between these servers was easy and efficient. AWS's flexibility and reliability ensured our infrastructure remained robust and scalable. Despite some network issues with UCF, where they shut down our website from their network, our website itself remained up and running. To avoid any problems during our demonstration, we used a mobile hotspot to view the website and communicate with the robot, even though it wasn't strictly necessary. AWS provided a reliable and flexible infrastructure that met our needs perfectly, allowing us to focus on delivering a smooth and functional demonstration of the Wrench Monkey project.

To handle the communication between the ESP32 device and our desktop and mobile applications, we implemented a RESTful API architecture along with WebSockets. The RESTful API operates on the principles of Representational State Transfer (REST), offering a standardized and well-researched approach to data communication. This API acts as a middleman, allowing the ESP32 device to interact with the MongoDB Atlas database and fetch or update data as needed. Each API endpoint corresponds to a specific function within the system, such as retrieving tool information or managing real-time status updates. These endpoints are designed to handle various types of requests, including GET (for fetching data), POST (for creating new data), PUT (for updating specific existing data), and DELETE (for removing existing data).

When the ESP32 device initiates communication with the API, it sends HTTP requests to the designated API endpoints. These requests contain structured data payloads in JSON format, holding information relevant to the intended operation. Upon receiving an HTTP request, the API performs several key tasks. First, it validates the incoming data to ensure its integrity, helping prevent unauthorized access or data manipulation. Next, the API processes the request by interpreting the payload and determining the appropriate database operations to execute. For example, if the request is to update a tool's status, the API translates this into an update query for the MongoDB Atlas database. Once the database operation is completed, the API formulates a response message containing the outcome of the request. This response, also in JSON format, includes relevant data or status codes such as 200, indicating the request was successful.

In addition to the RESTful API, we utilized WebSockets to maintain a constant stream of data between the AWS backend server and the AWS frontend/database. WebSockets provide full-duplex communication channels over a single TCP connection, enabling real-time updates and continuous synchronization between the server and clients. This technology allows for bidirectional communication, meaning that both the server and the client can send and receive data simultaneously without the need for repeated HTTP requests.

The implementation of WebSockets was crucial for ensuring the system remains responsive and up-to-date with minimal latency. With WebSockets, the server can push updates to the client instantly as changes occur, rather than the client having to poll the server for updates at regular intervals. This reduces the overhead associated with continuous HTTP requests and results in a more efficient and faster communication process.

To set up the WebSocket connection, we configured the AWS backend server to handle WebSocket requests and established a protocol for managing connections, messages, and disconnections. This setup included authentication mechanisms to ensure that only authorized clients could establish a WebSocket connection, thereby maintaining the security and integrity of the communication channel.

Overall, the bi-directional communication flow between the ESP32 device, RESTful API endpoints, WebSockets, and MongoDB Atlas database forms a robust and efficient data exchange mechanism. This, in turn, allows for real-time synchronization and seamless integration with web-based interfaces, contributing to the overall functionality of the Wrench Monkey's backend infrastructure. To illustrate this process, the diagram below labeled as Image 7.7 shows the comprehensive data transfer pathways. This diagram represents the routes through which data travels, starting from the ESP32 device's interactions with the RESTful API endpoints to the backend operations conducted on our MongoDB Atlas cluster and real-time updates via WebSockets.

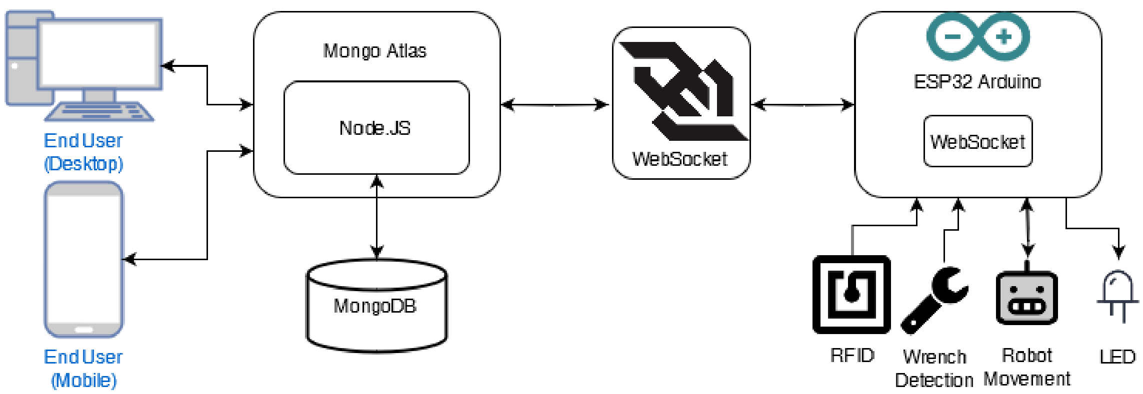

Image 7.7: Data Transfer Diagram (Atlas to Websocket to ESP32)

Section 7.2: Arduino IDE

The Wrench Monkey project is using the ESP32 microcontroller used as a versatile and powerful platform for many IoT, or Internet of Things, applications. This microcontroller is often programmed using the Arduino Integrated Development Environment, or Arduino IDE. The Arduino IDE was created in 2005 to provide a simple, low cost way to program a microcontroller. It has since grown to become a very popular development tool for microcontroller programming. The IDE provides a free, user-friendly environment to program compatible boards, as well as many libraries that are available to download to help simplify the coding process.

The Arduino IDE utilizes the coding language C++, which is a commonly known high level language. It was originally created in the 1980s as an extension of the C programming language. The C++ programming language is known for aspects such as its performance, its scalability, its flexibility, as well as the fact that it has a standard library. For these reasons, as well as other benefits, it is a well known and widely accepted programming language to learn and utilize, both in industry and for amateur programmers. This makes the Arduino IDE simple to learn and begin using as it does not require knowledge of a new or uncommon coding language.

On top of that, Arduino comes preloaded with many libraries that streamline the coding process. These libraries offer various functionalities and device drivers, enabling developers to leverage pre-written code snippets for taste such as sensor interfacing, communication protocols, and motor control. The library ecosystem significantly speeds up development timelines, allowing people to focus more on innovation and less on low-level programming. Throughout this project, we utilized many of these libraries' example code to interact with new sensors and test their usefulness for our project.

Within this project, the Arduino IDE is used to program the ESP32 microcontroller. It was extremely useful in the testing phase of the project, as there were libraries available to download for many of the different components that are being used. This helped simplify the coding process, as there were many functions that were ready to use, allowing the team to simply begin testing and integrating components.

Section 7.2.1: Movement

When it comes to movement in the Wrench Monkey project using the aforementioned Arduino IDE and ESP32 microcontroller, and the physical components of the tool chest. The primary objective is to smooth the path for controlled and precise movement of the tool chest within its controlled environment while implementing robust obstacle avoidance mechanisms through an ultrasonic sensor.

In our project, the movement of the tool chest is not just about making it from point A to point B, but instead making sure the movement is smooth, controlled, and precise. The main reason for this is safety, as the tool chest is heavy in nature and heavier when we load up our sample tool set and a battery. In the real world, should this project take on more facilities, it must be able to navigate tight spaces while making sure nothing or nobody is in its way. For that reason we decided to take advantage of an ultrasonic sensor mounted on the front middle section of the robot. The sensor is wired in such a way that if it detects an object within five inches of the tool chest’s range, it will stop in its tracks and not move until the object or person has been moved. Once the object is cleared out of the way or, in the case the obstruction cannot be moved, the user will have to re-command the device to go to a certain station. This fallback mechanism ensures that the Wrench Monkey can adapt to unforeseen circumstances and continue its operation efficiently.

Additionally, to address any unforeseen emergencies or system malfunctions, we have incorporated a digital emergency stop button on both the desktop website and mobile application. This button serves as a last resort fail-safe mechanism that allows users or operators to instantly halt all operations and shut down the device in case of critical situations. Should the website or database fail to tell the robot to stop, there is always a physical on/off switch positioned next to the main PCB. The robot generally moves slow enough, due to safety constraints, that turning it off will never be a problem.

Beyond the safety systems in place, the algorithms used for controlling the robot are depicted in section 7.2.2, as we show the line following techniques we tried, and the ones we decided on. To ensure the functionality of the motors, we were able to conduct testing by using Arduino example code. This involved setting the output value of input 1 to high and input 2 to low for forward motion, and conversely setting input 1 to low and input 2 to high to initiate reverse motion. The initial tests gave us a basic understanding of the motor control logic needed to maneuver the robot effectively.

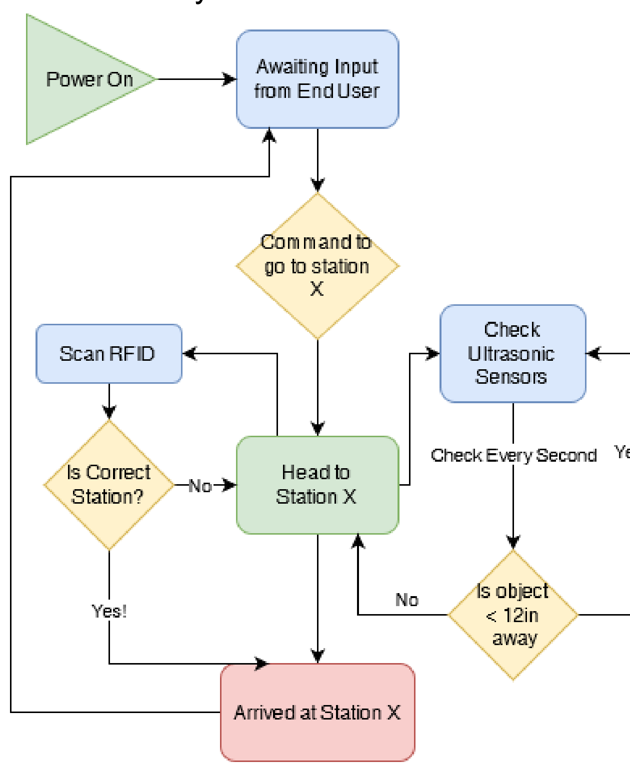

Image 7.8: State Diagram for Basic Movement

Lastly, within the state diagram depicted in Image 7.8, shown above, we illustrate the movements of the robot. This diagram serves as a visual representation of the algorithms and logic governing the robot's behavior, showcasing the transition between different states during its operation. By combining practical testing with theoretical frameworks represented in the state diagram, we gain valuable insights into the workings of the robot's control system. This allows us to ultimately achieve a high level of accuracy and reliability in the robot's navigation.

Section 7.2.2: Line Following

In terms of software development for Wrench Monkey, there are two large testing phases–the first phase using bang-bang control and the second using PID control. The first phase began with bang-bang control because, as mentioned in the research section, it is the simplest controller type that can be implemented and it allows for quick testing of the sensors, motors, and MCU working in conjunction with each other.

To implement bang-bang control on software, we wrote simple functions for going straight, veering left, and veering right. In the main loop, conditional statements are used to check the digital outputs of the IR sensors. If the line is being detected on one of the outer sensors then the appropriate function is used to turn in the direction that causes the line to be detected by the sensor at the center of the sensor array.

Before moving to explaining the software implementation of PID control, it is worth mentioning that the PWM capability of the ESP32 module is used for varying motor speed. With the inclusion of the H-bridge in our control system circuit, we are able to test various methods of turning. More specifically, the implementation of PWM would allow for slight direction adjustments by simply reducing the speed of one of the motors, while the H-bridge would be used for more drastic turns when the main path branches off into multiple paths. From the software perspective, the H-bridge would be implemented by bringing the enable pins high or low which would change the polarity of the motors, hence, changing the direction of rotation.

After testing the line following functionality using the bang-bang control, the PID controller was implemented. As described in the research section of this paper, PID control uses negative feedback to generate an error signal to which various mathematical operations are performed such that a desired control signal is generated for proper system control. That being said, the main loop obtains the approximate position of the line using the IR sensors; this measured position is the reference signal and an approximated distance from the central sensor is used as the error signal that was just described. Next, the error value is passed into a PID function that stores the error signal, increment the integral term by the amount of error (this is the discrete version of integration), and get the difference between the current error and the previous error (the previous error is stored in a global variable that can be updated after each iteration of the PID function). A linear combination of the calculated values is then taken using the set PID

coefficients. The resulting value is added to the speed of one motor and subtracted from the other motor.
We decided to use a combination of both PID and Bang-Bang control to enhance the robot's line-following capability and minimize veering from the line. Initially, Bang-Bang control was employed due to its simplicity and effectiveness in quickly testing the basic functionalities of the sensors, motors, and microcontroller unit (MCU). However, while Bang-Bang control is straightforward and provides a good starting point, it lacks the finesse required for precise line following, especially when dealing with curves or slight deviations.

To address these limitations, we integrated PID control into our system. PID control, with its ability to use proportional, integral, and derivative calculations, offers a more refined approach. By continuously adjusting the motor speeds based on the error signal (the difference between the desired and actual positions), PID control smooths out the robot's movements, ensuring more accurate and stable line tracking.

In practice, this hybrid approach means that the robot can quickly react to large deviations from the line using Bang-Bang control, while PID control fine-tunes the adjustments to keep the robot centered on the line. This combination leverages the strengths of both control methods, resulting in a robust and responsive line-following mechanism. The flexibility of PWM control and the directional capabilities provided by the H-bridge further enhance this system, allowing for both subtle and significant directional changes as needed. This dual approach ensures that the robot can handle various scenarios effectively, from straight paths to intricate curves and intersections.

Section 7.2.3: Tool Detection: Pressure Sensor

In order to highlight which tool is requested, a WS2812B LED strip, which is individually addressable, is programmed through the Arduino IDE. This is done using the Adafruit Neopixel library. First the LED strip is declared in the code, specifying the type of LEDs, the number of LEDs on the strip, and the pin on the ESP32 to which data in wire is connected. The pin to which the pressure sensors are set is also declared here. Next, in the setup loop, the LED strip is initialized and all pixels are turned off to begin. In addition to this, the brightness of the LEDs is set and the baud rate for the pressure sensors is initialized.

In the main body of the code, there are if statements. These statements state that if the pressure sensor reads a value of 20 or more, that means that the tool is present in the drawer. If this is true and the tool is requested, then the strip.setPixelColor function is used to declare which LEDs are to be turned on, and the color to which they should be, which in this case is green. Once the tool is removed and the pressure sensor drops to a reading below 20, the LED turns red. The strip.show function is also needed here to turn on the LED to the settings described in the strip.setPixelColor function.

Section 7.2.4: Tool Detection: RFID

For the tools equipped with RFID stickers, the stickers are read using the MFRC522 library in the Arduino IDE. To read the data, first, the reset pin and slave select pins are defined and linked to the appropriate pins on the ESP32. Then the board is initialized.

The main code continuously scanned for RFID signals, always checking for tags within range. This was done by placing the RFID reading logic inside the main loop, so the system constantly monitored for new signals. When a signal was detected, the system read the sticker's data and compared it to the expected data stored in memory. If the data matched, the tool was registered as returned, triggering a series of actions like updating the tool's status and possibly sending a confirmation to the central server. If the data didn't match, the system identified the incorrect tool placement, and the corresponding LED turned red to indicate the wrong spot. This visual alert was crucial for quickly correcting mistakes.

The RFID system also managed tool requests. When a tool was requested, the corresponding LED turned green, guiding the user to the correct tool. Upon removal of the tool, the RFID reader stopped detecting the signal, and the LED turned red to indicate the tool was taken. This immediate feedback helped avoid confusion about tool status.

Throughout development, we faced significant challenges due to lack of documentation and conflicting information about the MFRC522 library and its integration with the ESP32. These gaps led to extensive trial and error, particularly in understanding the correct initialization sequences and RFID signal handling. Conflicting online information further complicated finding reliable solutions.

We used continuous scanning by placing the RFID read function in the main loop, ensuring the system always checked for RFID tags. To halt scanning when necessary, such as during tool requests or returns, we implemented logic to temporarily pause and resume RFID reading. Traditional Arduino delay() commands caused issues by halting all operations for a specified duration, leading to missed RFID signals and unreliable readings. We addressed this by using the millis() function, which returns the number of milliseconds since the program started, allowing non-blocking delays. This method let us maintain continuous scanning while introducing necessary pauses, keeping the RFID system responsive and accurate.

In summary, the RFID tool detection system was a vital part of the tool management system. Despite the challenges from inadequate documentation and conflicting information, we developed a robust solution through continuous scanning and non-blocking delays. This ensured reliable tool tracking, accurate identification, and effective management within the system.

Chapter 8: System Fabrication and Assembly

The following chapter details the process by which the custom printed circuit boards, or PCBs, were designed for testing and final use. The Wrench Monkey will come equipped with a single custom PCB, however an additional prototype PCB was designed and created for the power delivery unit in order to allow for testing of those components. The first PCB discussed here is the PDU prototype board, and the second PCB discussed is the main PCB that is used in the final design of the Wrench Monkey.

This chapter also discusses the custom hardware that was designed and 3D printed. In order to save on costs and ensure that the pieces would meet our exact size requirements, custom mounts were made for the motors, one of the RFID tags, the infrared sensor array, and also the PCB itself. It will also discuss how the toolbox was assembled for testing.

8.1: Main Control Board

The PCB is the central component in Wrench Monkey that is for navigation between workstations and accomplishing other tasks. The ESP32 is the main component in charge of communicating with other devices such as the computers and phones that will be requesting, via Wi-Fi, for tools to be sent to a desired workstation. In addition to being able to communicate to other devices, the ESP32 is used for the software implementation of the controllers. For example, the ESP32 is performing the calculations dealing with the PID control technique and sending the resulting control signals to the H-bridge. This means that the calculated values are used to generate the appropriate PWM frequencies to send to the H-bridge and also determine the motor rotation direction when a turn must be taken to get to the desired workstation.

The next, major component on the PCB prototype is the H-bridge which is located at the center of the board because of how many connections are made to it. The L298 H-bridge was chosen because it can be used to change the polarity for two motors and also because its enable pins allow for the implementation of PWM control signals. That being said, the L298 allows for both the polarity switching and the speed varying of the motors.

The next major section of the PCB is the tool detection section. An important feature of the Wrench Monkey is it's ability to detect the presence of tools and communicate that to the user. To accomplish this, header pins for RFID readers, an individually addressable LED strip, and pressure sensors are included on this board. The choice to use header pins allows the flexibility to place these three components within the drawer while the PCB can be placed on top of the toolbox.

For the power delivery section of this PCB, the contents of the power delivery unit prototype board previously mentioned are added to this main PCB board so that all components are included on a single board.

To aid in the navigation of the Wrench Monkey, a five sensor array of infrared sensors and an RFID reader are mounted to the bottom of the chassis. The IR sensors are utilized to enable the line following method of navigation, and the RFID reader is used to detect when the toolbox has reached the desired station by placing an RFID tag beneath the line at each workstation. There is also an ultrasonic sensor mounted to the front of the toolbox to allow for a safety measure to be implemented, in which the toolbox will pause it’s motion if it detects anything in its path.

Along the outer edges of the board, the header pins can be seen for the various sensors. There are in total three RFID sensors, one infrared sensor array, two pressure sensors, one ultrasonic sensor, one set of LEDs, and connections for the motors. Header pins are used here as it allows the various sensors and components to be placed at various parts of the toolbox as the wire length could be adjusted, while the PCB could be located at the top of the toolbox. The labels on the board’s silkscreen are in place to make sure connections are made correctly. There are also LEDs placed on the board to make testing and troubleshooting simpler. There is an LED that represents power, one that turns on when the board is receiving information, and one that turns on when it is transmitting information.

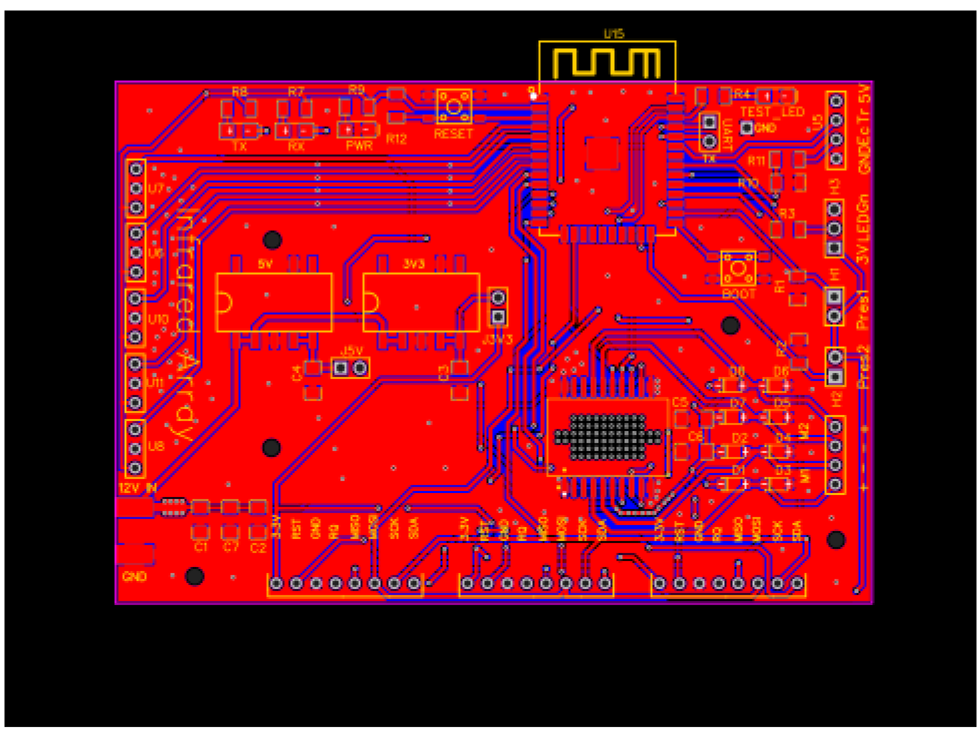

Image 8.1: Custom PCB

8.2 Custom Hardware

To complete this project, there were multiple parts, designed in Onshape, which were 3D printed. These parts were used to mount various sensors and parts to the bottom of the chassis. Custom mounts for the motors were designed, as well as a mount for the RFID reader and a mount for the IR sensor array. Additionally, there was a base designed for the custom PCB. Designing these mounts with the intent of being 3D printed was beneficial as it helped keep the price of materials low, as well as allowing the for the parts to be the exact heights and sizes that were needed to help the Wrench Monkey function properly, as well as making the end product look more professional.

8.2.1 Motor Mounts

To attach the motors to the bottom of the chassis, mounting brackets were designed. As the Wrench Monkey is front wheel drive only, there were two motors which needed mounts. The mounts were created and printed in order to provide extra reinforcement when attaching the motors to the chassis to prevent the provided metal mounts from bending. These mounting brackets are cylinders designed with open ends to fit the motor within it on one side, and to leave the jumper cables available on the other side to allow them to connect to the PCB. They mount on the bottom of the chassis in the front, and are mounted with screws. To allow for the screws, there are small extensions on the side of the cylinder where holes were placed to allow for more secure mounting to the chassis.

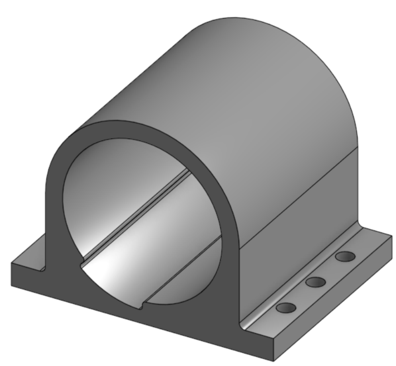

Image 8.2: Motor Mount to Chassis

8.2.2 RFID Mount

In order to provide the Wrench Monkey with the ability to stop at the correct workstation, an RFID sensor is mounted to the bottom of the chassis, and RFID tokens are placed below the line that the robot follows. In order to attach the RFID sensor, a mount was created with a solid base approximately the size of the sensor, and four extruded columns that lined up with the screw holes on the sensor. The column height was adjusted so that it was high enough that it would be hovering above the ground, but it was low enough that the sensor would be able to pick up the RFID signal. This mount is attached to the bottom of the chassis, centered and on the front, using double sided tape.

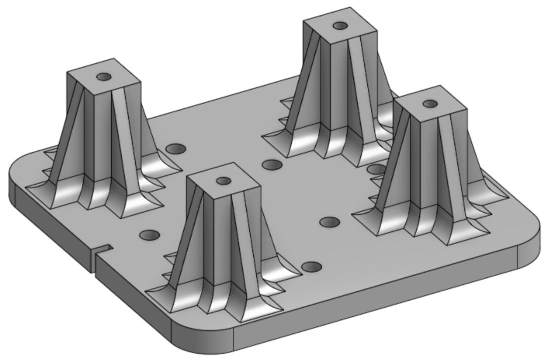

Image 8.3: RFID Mount to Chassis

8.2.3 Infrared Sensor Array Mount

The infrared sensor array is used in order to allow for PID controls to be implemented, which allows for accurate line following. To mount this to the base of the chassis, a mount is created. This mount is created with a solid base, approximately the size of the sensor, and two long ovals extruded up in order to screw in the infrared sensor array. Similar to the RFID mount, the height of the extruded portion was tuned so that the sensor would not be too close to the ground that it could catch on something, however it would also be low enough to accurately detect the line on the floor. This sensor was placed on the underside of the chassis, centered directly behind the RFID sensor mount.

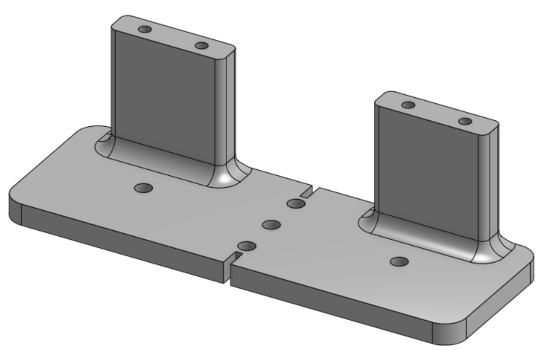

Image 8.4: IR Array Mount to Chassis

8.2.4 PCB Enclosure

To securely attach the PCB to the Wrench Monkey, there was a base designed. This allowed the PCB to be kept safe, allowing it to be secured on the top of the toolbox. The base is designed as a rectangle the size of the PCB, and it has tall enough walls that the PCB is prevented from falling or sliding out. There is a small hole cut out at one part to allow for the ESP32 antenna to fit through, as it slightly hangs off the edge of the board. There is also a cutout on the side to allow the power and ground wires to attach to the board flat, but still fit within the enclosure. This mount is attached via double sided tape to the top of the toolbox to ensure it does not move around while the toolbox is in motion.

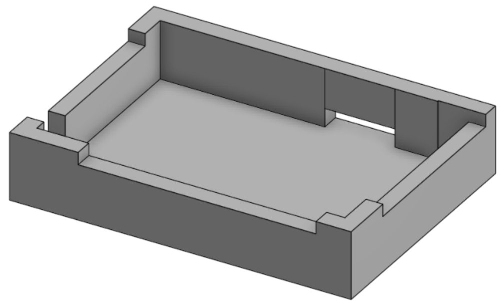

Image 8.5: PCB Enclosure Mount to Toolbox

8.3 Project Assembly

The following section explains how the Wrench Monkey was assembled for testing. The chassis is assembled first, then the tool detection system within the drawer is assembled.

8.3.1 Chassis Assembly

The first part of the project to be assembled was the chassis. The base of the chassis is made using a plywood board. The Wrench Monkey is front wheel drive, so on the front of the chassis the two motors and front wheels were secured using screws and a custom 3D printed mount. The back two wheels were secured on the back of the chassis without motors. Next the RFID sensor was secured to the custom 3D printed mount with small screws, and the mount is secured to the bottom of the chassis along the front using double sided tape. The five sensor IR array is also secured in the same way, using it's own custom 3D printed mount, directly behind the RFID reader. To the front of the chassis, the ultrasonic sensor is secured using double sided tape. A hole is then drilled in the chassis to allow the 12 volt and ground wires to be fed through the bottom of the chassis, and up through the bottom of the toolbox to where the battery is stored.

8.3.2 Tool Detection System Assembly

To assemble the tool detection system, first the foam cutouts were made for each tool so that they would have their designated spot and not slide around while the toolbox is traveling between stations. Next, holes are cut out in the front of the foam to allow for the labels of the tools to be placed. After all of the holes are cut in the foam, the pressure sensors are placed within the holes of the two slots made for the wrenches. The RFID readers are placed beneath a thinner layer of foam, located beneath the holes for the two sets of pliers. The RFID readers are placed beneath this layer to both add a layer of protection from the tool, and also to hide them so that the inside of the drawer looks cleaner. There are also additional pieces of foam placed beneath this layer so the tools are elevated more, and the metal of the toolbox drawer does not interfere with the RFID signals. There are small RFID stickers placed on both sides of the pliers so that the tag is correctly read even if the pliers are placed upside down. An individually addressable LED strip is placed along the base of the foam, beneath the cutouts for the tool labels, and the transparent labels are placed in their positions so the light shines through.

8.3.3 Overall System Assembly

To assemble the overall system, the toolbox is placed on the chassis and the tool detection system is placed within the top drawer. The battery resides in the bottom door of the toolbox, and the PCB along with the fan to provide external cooling for the h-bridge, are placed on the top of the toolbox.

Chapter 9: System Testing and Evaluation

The following chapter includes details on how the different subsystems within the Wrench Monkey were designed and tested. The testing of all the different subsystems was completed in stages. To begin, each component was tested individually to determine that it would work. Then all of the components within the subsystem were slowly integrated together, testing at each step along the way, to ensure that the final product would work. This also allowed for easier identification of any issues that came up as slowly integrating each component individually ensures that when something doesn't work, it is easier to identify which aspect of the subsystem is not performing as expected. Once all of the subsystems, hardware and software, were completed and working individually, they were integrated together so that Wrench Monkey can now contain all the desired features and functionalities, and can perform the desired tasks as one complete system.

Section 9.1: Line Following

For the line following portion of Wrench Monkey, in the case of using/testing the IR sensors, they would first need to be calibrated to output the correct output. To do this, code must be written that shows the output of the IR sensors over time and if they are not reading the correct values then the potentiometers can be adjusted accordingly. Similarly, the color sensors can be calibrated by using a code that displays numerical values corresponding to the red, green, and blue components of the reflected light. Once the values are being displayed, the sensors must be placed over a white surface to obtain the maximum values and then they must be placed over a black surface to measure the minimum values that are to be read. Then the values are to be mapped to values between 0 and 255 which are used by the system to determine when the line is below the sensor

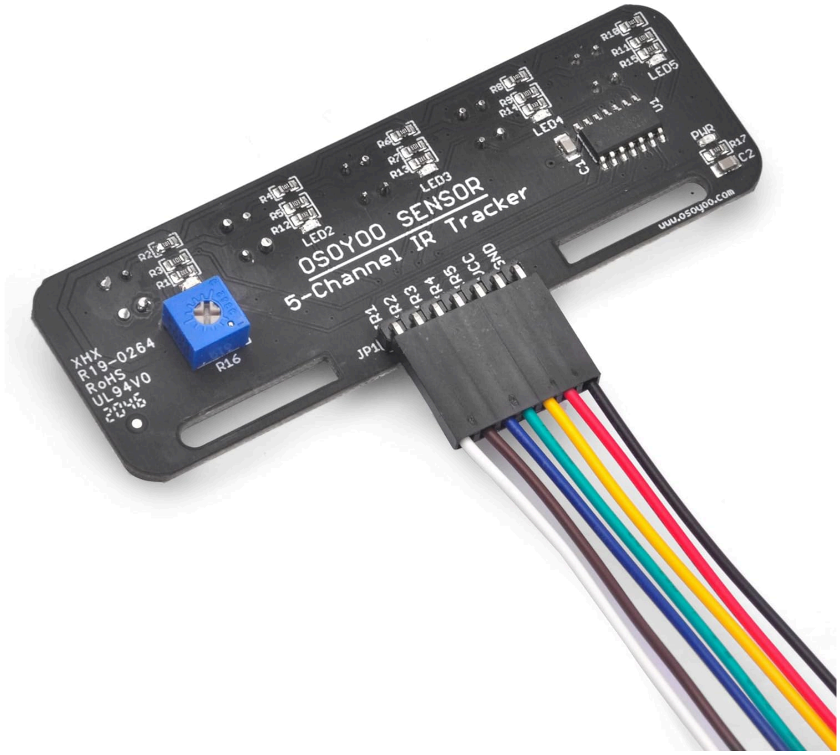

Image 9.1: IR Sensor

After sensor calibration, the next step would be the implementation of the control algorithm for the simple case of line following with no forks in the path. For initial testing purposes, the bang-bang control technique could be easily applied by simply allowing for the motors to run at the same speed and then slow down, or even stop, a motor when the line detection sensors determine that the Wrench Monkey is veering off the path so that Wrench Monkey would steer back onto the correct path. Once the basic functionality of the system such as steering, line sensing, and motor control are implemented, the PID control can then be tested. Since the ESP32 has Bluetooth/Wi-Fi capabilities, the PID parameter can be changed using a simple user interface on a phone or computer to tune the controller so that the desired behavior is displayed. The main parameters to be changed would be the gains for the proportional, integral, and derivative terms of the PID controller. These terms would then be used to scale the error, the integral of the error, and its derivative.

The next step for line following development and testing would be the implementation of conditional statements that would be used for navigating the path branches which lead to the different work stations. In the case that the IR sensors are selected for the line following system, an RFID reader is used to detect at what branches Wrench Monkey must turn. For this to work, the RFID reader would simply need to read the RFID tag ID which would correspond to the workstation associated with that branch. In terms of software, this means that when the Wrench Monkey is called to a certain workstation, it will search for the corresponding RFID tag.

If the color sensors are chosen for the line following functionality of Wrench Monkey, then an RFID reader would not need to be implemented because the line colors can be used to identify which workstation the path leads to. In terms of the code, a conditional statement will check for a range of values that correspond to the color associated with the desired workstation. The color value for this method would only be checked from one of the outer color sensors in the sensor array because the current path that Wrench Monkey is following will not be of interest. In other words, only the paths that branch out from the current path are checked.

Finally, to further enhance the system path following, the ultrasonic sensor is tested by placing an object in front of Wrench Monkey. The object is placed at varying positions to determine the distance limits for object detection and to determine if more ultrasonic sensors are needed to successfully avoid crashing into path obstructions.

All in all, multiple steps are implemented when testing the control system design to make it easier to determine where the faults lie. The bang-bang control implementation is used as a rudimentary test for hardware functionality for components such as the IR sensors and the motors. The main reason for performing a test on the motors is not only to test whether the connections have been properly made, but also to better understand what the motor control signal bounds should be when programming the ESP32. Once the sensor and motor operation are tested, the PID control testing is done with simple paths with no branches to focus on the path following without the same jagged behavior that is seen when using bang-bang control.

Section 9.2: Transportation with Load

To determine the feasibility of transporting a significant load on with the selected motors, the ends of two cords were attached to the two motors, and the other ends of the cords were attached to the base of the toolbox (which contained a book bag filled with textbooks). Upon securing both ends of the ropes as described, the motors were connected to a power supply to attempt to simulate moving the toolbox under load as shown in the image below.

Image 9.2: Initial Motor Testing

After the initial tests that were performed as shown, the base of Wrench Monkey was built and once again the motor performance was tested to prevent inadequate torque from limiting the project progress. In the test following the construction of the base, the toolbox was then placed on top of the base–once again with the bookbag load.

Image 9.3: Second Motor Test

Section 9.3: Tool Detection

The Wrench Monkey utilizes two different methods of detecting if a tool is present. The first method is by using a pressure sensor, and the second method is by using RFID stickers on the tool handles in conjunction with RFID readers.

There are four tools in the drawer, and there are two tools used with each method. Below is an image of the tool tray. The leftmost 2 tools are pliers, which utilize RFID for tool detection. The rightmost 2 are wrenches, and utilize resistive strain gauges for tool detection

Section 9.3.1: Tool Detection: Pressure Sensor

To test the effectiveness of the pressure sensors to detect the presence of tools, the pressure sensors were first connected to the ESP32 microcontroller via jumper cables and a breadboard. Next, code was written within the Arduino IDE and uploaded to the ESP32, and the readings from the sensor were seen in the serial monitor.

The individually addressable LED strip was then also connected to the microcontroller and tested to see if it worked. The code to test the LED strip was also completed using the Arduino IDE. Code was then written to connect the pressure sensor to the LED strip such that when the sensor read above a certain value, a section of the LED strip would change colors, and each pressure sensor controlled a different set of LEDs.

Finally, the craft foam that makes up the tray insert was cut to fit the tools, and the sensor was placed between the two layers of foam. Then the tools were placed in their respective spots to determine what reading they would give when present to fine tune the code, allowing it to effectively determine if a tool has been removed or returned.

Section 9.3.2: Tool Detection: RFID

To test the RFID reader, it was connected to the ESP32 microcontroller via jumper cables and a breadboard. Next, the code is written to read the contents of the stickers. Once it is confirmed that the contents are being read correctly, each set of data can be recorded and matched with a different tool. With this information, it can be known if the tool is present, missing, or in the incorrect spot in the drawer. This is also connected to the LEDs so that a section of LEDs can change color depending on the status of a tool.

Image 9.4: Tool Detection Tray

Section 9.4: Sending Commands to ESP32 via Website

In this section we embarked into the testing phase focused on sending commands to the ESP32 microcontroller via a website interface. I do want to acknowledge that this test represents a scaled down version of the full-scale implementation planned for this microcontroller; however, this test serves as a crucial step in verifying its operability.

The initial step of this test involved configuring the ESP32 in Access Point (AP) mode. Although the final project utilizes station mode, which allows the ESP32 to connect to a local wireless network, conducting this test in access point mode allowed for a controlled environment to assess basic functionality. Using the example script from the ESP32 library, I set up the microcontroller in AP mode, established an SSID named “Test Project” with a password of “password” and created a basic website interface with HTML elements. Using HTML, I was able to make a straightforward header and descriptive text, complemented by a button to control an LED connected in series with a resistor via my breadboard.

Crafting the code involved defining the pin mode and initiating the local Wi-Fi server, alongside coding the button’s behavior to toggle the LED’s state. This task was accomplished through a simple if-else statement. If the button was pushed the code would digitally write to the LED’s pin as high, otherwise it would write as low. Once the LED entered a certain mode I had to rewrite the button logic so it would display the opposite action. For example, if I clicked the button to the on state and the LED turned on, the button would now read as turned off.

Upon deploying the code to the ESP32 and connecting to its local network (named “LED Test”), accessing the web page at the default gateway IP address (192.168.1.1) revealed the interactive interface. By clicking the button on the web page, I could instantly toggle the state of the LED showcasing the effective communication between the web interface and the microcontroller. While this demonstration was basic in nature, its successful execution validated the feasibility of sending commands from a web interface to the ESP32 microcontroller.

Section 9.5: Senior Design 2

Senior Design 1 provided the opportunity to design a project and perform research in order to prepare to complete the project. In Senior Design 1, we designed a smart toolbox that we called the Wrench Monkey. We also had the chance to purchase and test individual components to be incorporated into the final product. We were also able to construct the chassis for the toolbox, testing that it would have enough torque and also be able to handle the weight of the final product. Finally, prototypes of the customized PCBs that are to be used were designed, and much of the documentation was written up in preparation for Senior Design 2.

In Senior Design 2, we continued with our testing and developing the software necessary to reach all of our goals set for the final product. This included testing components such as the ultrasonic sensors and the IR sensors, RFID sensors, and strain gauges, and learning how to make them work within our project.

We also ordered the custom PCBs and assembled them to implement in Wrench Monkey. A total of 2 boards were fabricated. A transparent PLA filament was also used to 3D print a custom designed tool label for the tool drawer insert. This is used to cover the LEDs and help dissipate the light emitted from them.

Once all of the subsystems were fully tested and they proved to be functional as individual parts, they were combined, incorporated and tested in the resulting product. With the combined subsystems put together, this allowed there to be fine tuning to the measurements taken from the sensors in order to provide a functional product. Details such as the height at which the ultrasonic sensors needed to be placed for effective readings and IR sensor array tuning were determined at this stage of development.

Finally, as described in the introductory sections, upon the completion of the project, Wrench Monkey was able to do the following: follow a set line path to arrive at desired workstation, stop if an object is obstructing the path, connect to the project’s website, have adjustable PID control coefficients, detect the presence of tools in the toolbox via RFID and strain gauges, and keep track of which user has a certain tool. These were all accomplished

Chapter 10: Administrative Content

This section provides a summary of the financial and scheduling aspects related to the Wrench Monkey project. It includes details on budget estimates, bill of materials, and work allocation for designing and constructing the Wrench Monkey.

Section 10.1: Budget and Financing

This section provides details on an item, the quantity of that item needed, its anticipated per unit cost, and the total anticipated cost for each part. It's important to note that the specific part prices for the project are not listed here; rather, this is an overview of the essential parts and devices required. From this budget table, it can be seen that the total estimated cost is less than $1000, hopefully around $309 as shown below. Each person in the group is expected to contribute exactly one quarter of the total final cost.

Item	Quantity	Expected Cost
Toolbox	1	15.00
Custom PCBs	1	15.00
MCU (ESP32)	1	3.00
Lead Acid 12v Battery	1	20.00
LED Strip (12ft)	1	15.00
RFID Sticker Roll	1	17.00
RFID Module	3	10.00
Ultrasonic Sensor	2	5.00
IR Sensor Array	1	12.00
Strain Gauge	2	15.00
H-Bridge (L298P)	3	30.00
Diodes (1N4007W)	100	1.00
Resistors	50	3.00
Capacitors	50	3.00
½x12x24in Birch Plywood	1	10.00
Block Insert Bearing	4	10.00
Uxcell Hex Coupler	4	10.00

Linear Motion Rods	2	10.00
Shaft Lock Collar	10	9.00
Tires	4	15.00
Hex Wheel Adapter	2	6.00
DC Geared-Down Motor	2	70.00
3D Printed Items	6	5.00

Total Estimated Cost	$309

Table 16: Estimated Budget

Section 10.2: Bill of Materials

This table contains a list of all of the items that were purchased to complete this project.

Item	Quantity	Unit Cost	Total
Toolbox	1	15.00	15.00
Custom PCBs	1	9.00	9.00
MCU (ESP32)	1	2.68	2.68
Lead Acid 12v Battery	1	19.00	19.00
LED Strip (12ft)	1	13.99	13.99
RFID Sticker Roll	1	16.59	16.59
RFID Module	3	3.00	9.00
Ultrasonic Sensor	2	2.00	4.00
IR Sensor Array	1	11.99	11.99
Strain Gauge	2	6.50	13.00
H-Bridge (L298P)	3	10.87	32.61
Diodes (1N4007W)	100	0.0063	0.63
Resistors	50	0.05	2.50
Capacitors	50	0.05	2.50
½x12x24in Birch Plywood	1	9.88	9.88
Block Insert Bearing	4	2.25	9.00

Uxcell Hex Coupler	4	2.50	10.00
Linear Motion Rods	2	4.25	8.00
Shaft Lock Collar	10	0.89	8.89
Tires	4	3.74	14.96
Hex Wheel Adapter	2	2.98	5.96
DC Geared-Down Motor	2	33.99	67.98
3D Printed Items	6	0.66	~4.00

Total Cost	$291.16

Table 17: Bill of Materials

Section 10.3: Project Milestones for Senior Design 1 and Senior Design 2

The table below shows the project milestones for the research and writing portion of this project.

Task	Description	Start Date	End Date
Recruiting	Getting all team members recruited	01/09/2024	01/09/2024
Project Topic	Having several in person meeting to decide on the project idea	01/11/2024	01/18/2024
D & C	Creating the second chapter, or the project proposal. (10 Pages Total)	01/18/2024	02/02/2024
Rough Draft	Writing the first 60 pages of our Senior Design document. (15 pages per person)	02/02/2024	03/29/2024
SD1 Final Document	Adding 60 more pages to the rough draft making it 120 pages total (30 pages per person)	03/29/2024	04/23/2024
CDR Presentation	A practice run for the CDR presentation slide deck.	05/17/2024	06/05/2024

Slides			
CDR Presentation Video	Practice group video for the CDR presentation video.	05/17/2024	06/05/2024
Midterm Demo Video	Midterm Demo explains progress thus far with some system integration.	06/05/2024	06/29/2024
Conference Paper	8 Page conference paper making it easier for reviewers to read.	07/01/2024	07/08/2024
Final Slides	Final presentation slide deck with completed images based on the CDR	07/01/2024	07/13/2024
Final Presentation	Final presentation video done in sections based on the CDR	07/01/2024	07/13/2024
Final Demo	Final demo video showing the three main specifications	07/01/2024	07/13/2024
In Person Demo	Demonstrate our project to review committee	07/17/2024	07/17/2024
SD2 Final Report	Final updated documentation of the entire project from start to finish.	06/01/2024	07/23/2024

Table 18: Research and Writing Milestones

The table below shows the project milestones for the designing and prototyping phases of this project.

Task	Description	Start Date	End Date
Drive System Design	Selection of drive system and CAD drawing of chassis.	2/05/2024	2/26/2024
Part Selection	Determine components that will best fit the needs of Wrench Monkey.	2/12/2024	3/05/2024
Subsystem Prototyping	Prototype the subsystems such as the motor control and	2/19/2024	3/11/2024

	sensor.		
PCB Design	Design control boards for the project (power, sensing, motor control).	3/18/2024	4/07/2024
Website Prototype	Creation of website that is used to request tools.	3/19/2024	4/04/2024
System Integration	Putting together all the subsystems. Testing all the subsystems.	4/08/2024	4/23/2024
Assembly of Chassis	Attaching all motors and 3D printed mounts to the base, along with attaching the toolbox.	04/24/2024	05/02/2024
Assembly of Drawer	Finalizing tool slots along with RFID and Strain Gauge Placement.	07/01/2024	07/04/2024
Final PCB Assembly	Using stencils and soldering to piece together two working PCBs	06/19/2024	06/21/2024
Final System Integration	Attaching all hardware pieces of Wrench Monkey together.	07/10/2024	07/11/2024
Final Arduino Code	Finalizing websocket arduino code establishing communication between backend server and robot.	07/03/2024	07/04/2024
Final Website Code	Creating desktop websites and hooking up all backend APIs.	07/10/2024	07/10/2024
Final Mobile Code	Creating Android applications and hooking up all backend APIs along with final design.	07/15/2024	07/16/2024

Table 19: Design and Prototype Milestones

Section 10.4: Work Distribution

This section details the distribution of work among team members during this project.

Section 10.4.1: Team Leader

As part of the recommendations for effective time management in Senior Design 1, we decided to elect a team leader to keep everyone on track. Our team leader for this project is Rachael Sak. Rachael's responsibilities as team leader include:

- Task Allocation: Assigning tasks to team members based on their skills, availability, and project requirements. Each team member will have a clear understanding of their responsibilities and deadlines.
- Progress Monitoring: Regularly monitoring the progress of each team member and the overall project timeline. Identification of any potential issues early on and takes necessary actions to address them.
- Communication Facilitation: Facilitating communication between team members and ensures everyone is informed about project updates, meetings, and important decisions.
- Documentation Oversight: Oversees the documentation process and verifies it is complete, accurate, and citations are made correctly.

Section 10.4.2: Discord/Group Chat

To optimize communication and teamwork among our team members, we chose to use both an SMS group chat and a private Discord server. Each platform offers unique advantages tailored to our Senior Design project.

As our primary source of communication, we utilized an SMS group chat instead of Discord. While Discord offers features such as large file sizes, instant messaging, and voice channels for easy communication, the SMS group chat was preferred for its direct reachability without requiring internet connection. Additionally, we implemented a Discord bot to automate progress tracking by requesting weekly updates from each team member every Monday morning in the form of the following three questions:

1. What did you do last week?
2. What will you do this week?
3. Are there any blockers or impediments preventing you from doing your work?

This combination of SMS messaging and Discord bot integration optimized our communication strategy, ensuring we would not get behind on tasks.

Section 10.4.3: Estimated Table of Work Distributions

Due to the dynamic nature of our project and the varying tasks involved, the table of work distributions among team members, shown below, is a rough estimate.

Task Description	Primary Team Member	Secondary Team Member
PCB Design	William Wandelt	Rachael S, Matthew C

Hardware Assembly	Rachael Sak	William Wandelt
Website Integration	Matthew Trump	N/A
Mobile App Integration	Matthew Trump	N/A
Hardware Integration	Matthew Crespo	Rachael Sak
Hardware Debugging	William Wandelt	Rachael S, Matthew C
Software Integration	Matthew Trump	Matthew Crespo
System Testing	Matthew T, Matthew C	Rachael S, William W
PCB Design	William Wandelt	Rachael S, Matthew C

Table 20: Work Distribution

Section 10.5: User Manual

The following manual will provide step by step instructions on how to operate the Wrench Monkey website, as well as how to operate the toolbox itself.

Section 10.5.1: Creating an Account

To create an account, go to the website http://wrenchmonkey.life, and navigate to the top right corner and select "Register." The following login prompt will appear to fill out name, toolbox number, email, and password. Once an account has been created, the website will automatically redirect to the login page to login to their new account.

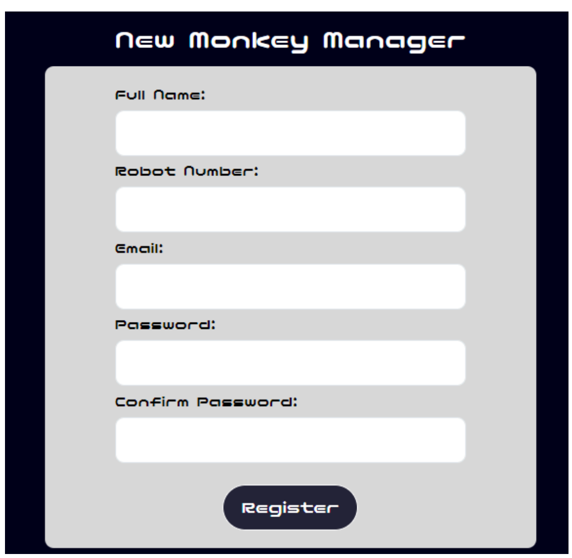

Image 10.1: Website Registration Page

Section 10.5.1: Using an Admin Account

The first user to create an account will have access to an admin account. This account will have unique functionalities such as the ability to create, edit, and delete tools and jobs. The admin dashboard is shown below

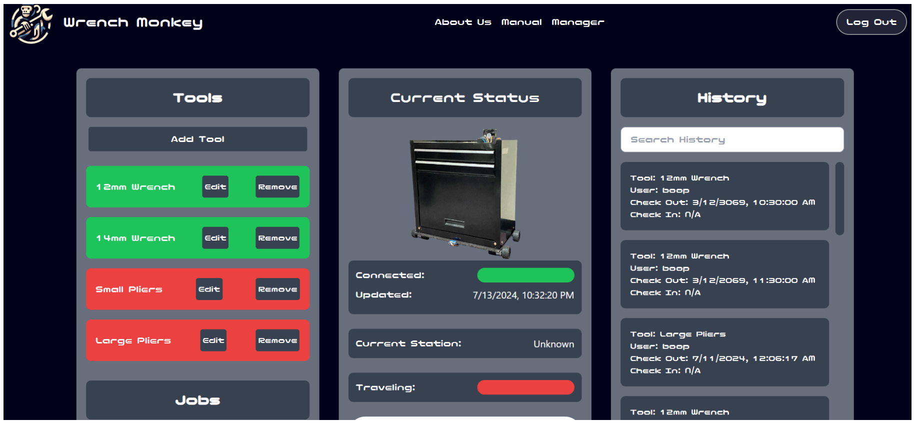

Image 10.2: Admin Account Dashboard

Section 10.5.1.1: Creating and Editing Tools

To create a new tool, select the “Add Tool” button that is located at the top of the leftmost “Tools” column. That will bring up the following prompt, which will ask for a tool name and a slot number.

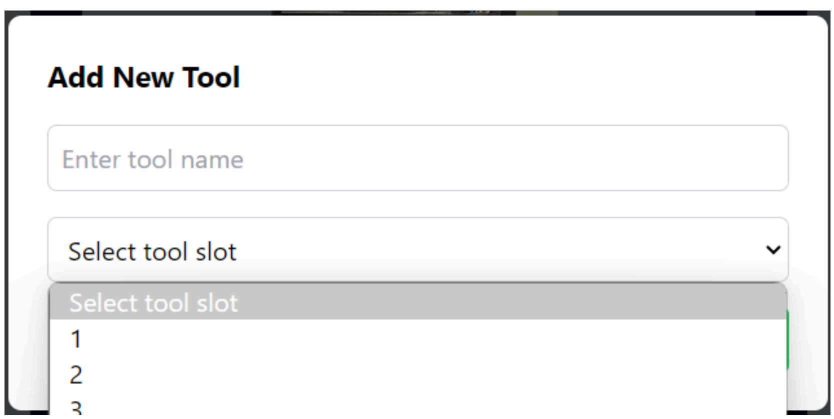

Image 10.3: Add Tool Screen

Selecting the “Edit” option next to an existing job will provide the option to change the name or the tool slot, and selecting “Remove” will remove the tool.

Section 10.5.1.2: Creating and Editing Jobs

Jobs can be created through the admin account to help streamline processes within the workspace. If there is a task that is often completed that needs a specific set of tools, a job can be created, which will request all the required tools at once and save the employee time. When the “Create Job” button is pressed, the following prompt will appear to name a job and select the required tools from the list.

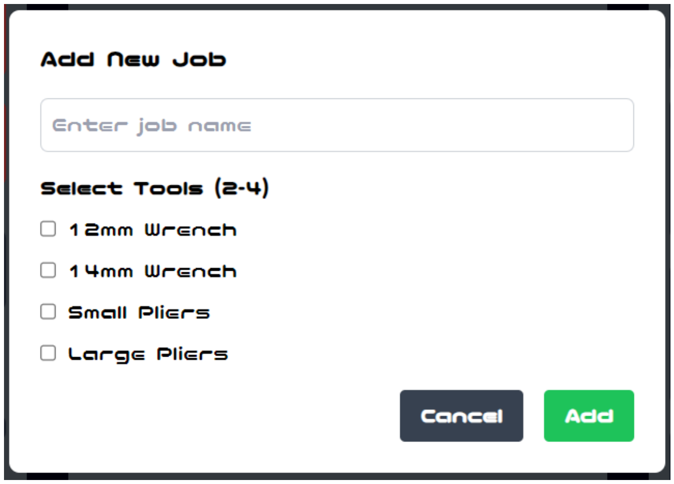

Image 10.4: New Job Prompt

If the “Remove” option is selected next to an existing job, that job will disappear for all users. If “Edit” is selected, a prompt will appear similar to the new job prompt, which allows the name of the job to be changed, and for tools to be added to or removed from the job.

Section 10.5.1: Using a Standard Users Account

A standard user account is used to request tools. It is also used to request the toolbox to travel to different stations. The dashboard is shown below.

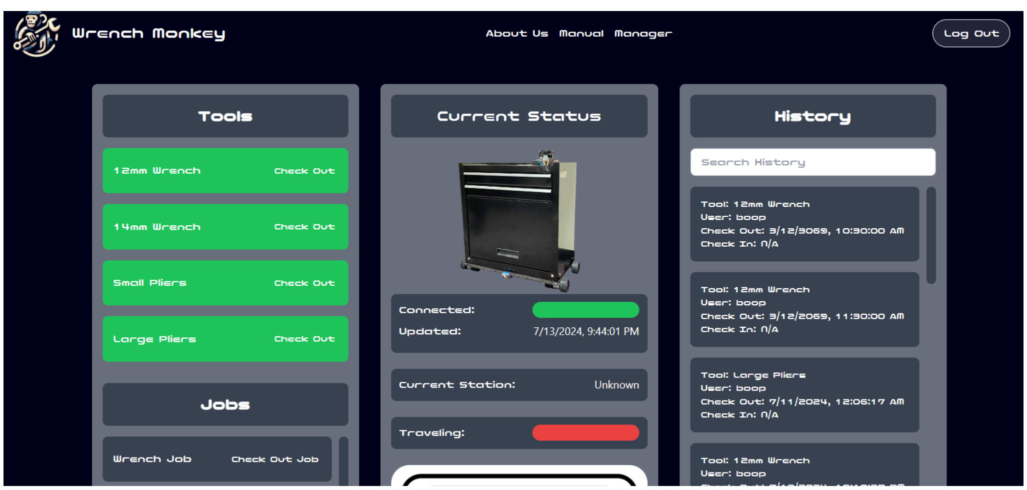

Figure 10.5: Standard User Account Dashboard

Section 10.5.1.2: Calling to a Workstation

To request the toolbox to travel to a specific workstation, scroll to the bottom of the center column. The current station is listed there, as well as a bar that is either red or green to signify if the toolbox is in motion. There are three buttons, labeled Station A through C. This section is shown on the left. Select the desired station, and the "Traveling" bar will turn green and a spinning gear appears on the track to show that the toolbox is in motion. An "Emergency Stop" Button also appears to quickly stop the toolbox if needed. An image of the screen when the toolbox is moving is shown on the right.

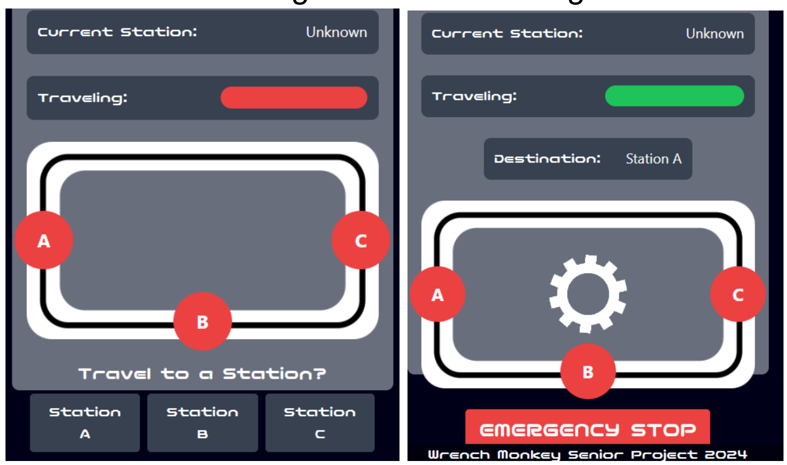

Figure 10.6: Requesting a Station

Section 10.5.1.2: Checking Out Tools

To check out a tool, navigate to the far left column to the "Tools" column. All the available tools will be listed there, and they will be highlighted green with a "Check Out" option if they are available, and red with a "Check In" option if they are not. Select the required tool, and then open the toolbox drawer. The LEDs located beneath the tool label will turn green to highlight the requested tool. After removing the tool, the LEDs will turn red before turning off. The tool name on the website will also change from green to red, and the "Check In" option will appear.

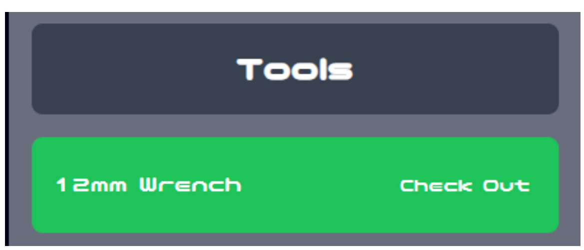

Figure 10.7: Checking Out Tools

Section 10.5.1.2: Checking Out Jobs

To check out a job, navigate to the leftmost column and scroll down to the "Jobs" section. In this section, all of the available jobs will be listed as shown below.

Image 10.8: Job Checkout

After selecting the job, the following prompt will appear. This will list the different tools that are included in that job, and ask for confirmation.

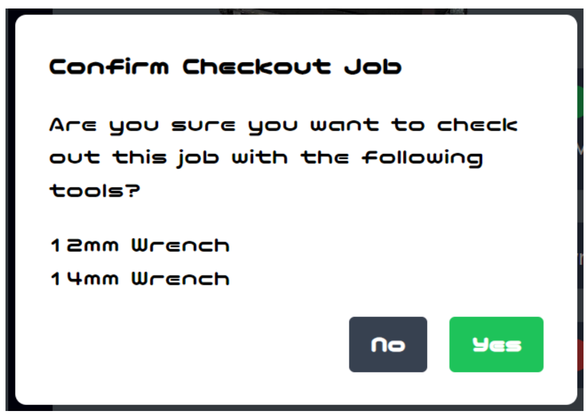

Image 10.9: Job Checkout Confirmation

After confirming, the LEDs that correspond to the first requested tool on the list will turn green until that tool has been removed from the drawer. After it has been removed, the LEDs will turn red, and the LEDs for the next tool will turn green. This will occur for each subsequent tool within that job until all tools have been removed from the drawer.

Section 10.5.1.2: Checking In Tools

To return a tool to the toolbox, navigate to the same section of the website. Similarly to checking out a tool, they select the "Check In" button. This will turn the LED within the drawer red to show the correct placement for the tool. For the tools that are detected via RFID sensors, placing the incorrect tool in the slot will cause the LEDs to flicker between blue and red until it has been removed. They will then turn back to red. Once the tool is replaced, the LEDs will turn green, and then off. The tool name on the website will also turn green, and the "Check In" option will change to "Check Out."

Image 10.10: Checking in Tools

Section 10.5.2: Setting up the Track

To set up the track all that is needed is a surface that is white and a thin black trace on top of the white surface. This can be done by placing printed sheets of paper with a black track on them, or by placing an electrical tape path between workstations. At each workstation, the appropriate RFID card should be placed underneath the line so the toolbox knows where each station is located.

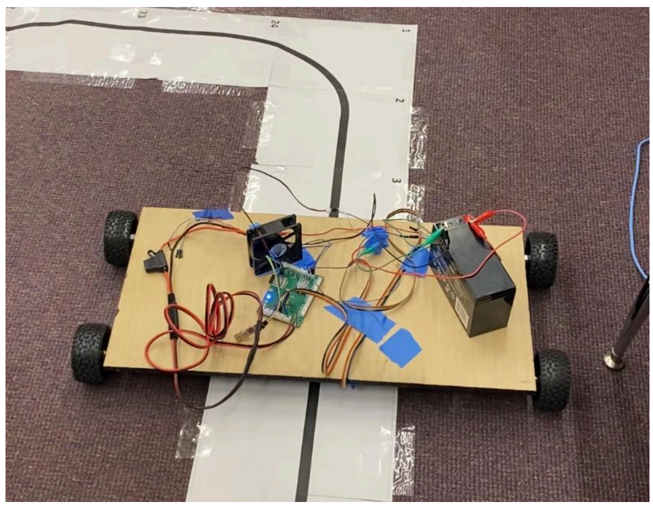

Image 10.11: Printed Line-Following Path

Chapter 11: Conclusion

As autonomous and semi-autonomous robots continue to be integrated into industrial environments, they are proving to be very beneficial in increasing productivity. Technology in a workplace can be extremely helpful in streamlining processes and making things easier for workers. Smart toolboxes have proved to be beneficial in industrial environments as they can help organize and track tools.

Products currently on the market have features such as automatic inventory, the ability to restrict access to only authorized users, and the ability to track which tool was taken by which user. This has proved beneficial as it not only helps companies keep track of tools so that they don't go missing, but it can also introduce an extra level of safety checks in environments where a tool left behind could cause a safety concern, such as a tool left within an engine.

The Wrench Monkey is a smart toolbox robot that will have multiple useful functionalities. It will have the ability to be called to multiple different workstations through the use of a web or mobile app, in which people could request specific tools, prompting the toolbox to come to them. It will also highlight the requested tools using LEDs to make finding the correct tool more simple, as well as be able to track if a tool is in the drawer or not. The tool detection capability will come from a combination of RFID stickers on the tool handles, paired with RFID readers in the drawers, as well as pressure sensors in the toolbox drawer.

Creating a smart toolbox like the one envisioned can be very beneficial to have in a workspace. Creating a robot that will come to the workstation of the person who requested it and deliver tools can increase productivity and efficiency as it prevents the need for workers to constantly get up to go locate a specific tool. Highlighting any requested tools can also be beneficial as it can help the user locate the item faster. For example, there are some tools, such as wrenches, that come in many different sizes, however they all look similar. If the needed size is known, highlighting the correct one will prevent the user from having to spend time searching for the right option.

Another benefit to the Wrench Monkey is its ability to track tools. When a tool is requested to a specific workstation and removed, the sensors within the drawer are able to identify that it is now missing. If the same tool is then requested at another workstation before it is replaced, there is a record of what workstation that person should go to to search for the requested item.

Another benefit of the Wrench Monkey is the flexibility it provides. The toolbox is equipped with IR sensors that are able to detect and navigate lines that are taped onto the floor, leading to the different workstations as well as the charging station. This provides the flexibility to change the path the Wrench Monkey will take, as well as the ability to route it to any workstation. This is beneficial as it allows for easy setup, as well as the ability to move it to a new environment or add workstations as needed. To ensure safety and prevent damage to the product, the toolbox will also be equipped with ultrasonic sensors so that it will stop and alert the users if there is anything blocking its path.

The Wrench Monkey web app also has the ability to set up tasks that are commonly completed and mark which tools are needed, saving said tools to the task. When a user wishes to complete that task, this will make it easy for them to request all of the necessary tools at once, without having to individually select each item. This could help streamline repetitive tasks as it further simplifies the tool request process.

In addition to its immediate benefits, the Wrench Monkey lays the foundation for a future where human-machine collaboration is not just a possibility but a necessity. As industries continue to evolve and adapt to changing market dynamics and technological advancements, the role of automation in augmenting human capabilities becomes increasingly pronounced. The Wrench Monkey exemplifies this symbiotic relationship, where robotic assistants alleviate mundane tasks and enable workers to focus on higher-level responsibilities that require creativity, critical thinking, and problem-solving skills.

Moreover, the success of the Wrench Monkey project underscores the importance of interdisciplinary collaboration and cross-functional expertise in driving innovation. From software developers and mechanical engineers to data scientists and industrial designers, the project brought together diverse skill sets and perspectives to overcome complex challenges and deliver a truly transformative solution. This interdisciplinary approach not only enriched the development process but also laid the groundwork for future collaborations and synergies across different domains.

Looking ahead, the widespread adoption of smart toolbox robots like the Wrench Monkey holds the promise of reshaping not just individual workplaces but entire industries. By harnessing the power of automation, data analytics, and human-centered design, organizations can unlock new levels of efficiency, productivity, and safety in their operations. As the Wrench Monkey continues to evolve and adapt to the ever-changing needs of the industrial landscape, it serves as a beacon of innovation, guiding the way towards a future where technology empowers humanity to achieve unprecedented heights of success and prosperity.

This document goes into detail about how this project was designed and built. It explains the process by which parts were chosen, as well as the testing and building process. This project has taught us a lot about how engineering projects work. Designing this project required us to research different existing products, as well as different sensors, equipment, and methods that could be incorporated into the project. It also required a lot of testing and troubleshooting be done to determine the viability of different options, as well as learning how to change directions when needed to adapt to unexpected challenges and find ways to meet our goals. This project has provided valuable experience on how to complete an engineering project from the design phase to the final product.

Throughout the course of the project, we were able to successfully reach all of our goals, as well as one stretch goal. The three stretch goals were the ability to use voice recognition and AI to request the toolbox without the website, the ability to identify if the correct tool is present through the use of unique RFID stickers on the tool handles, and the ability to wirelessly charge the toolbox. The RFID identification method was successfully implemented, however the vocal recognition and the wireless charging were not implemented due to time constraints.

We hereby declare that we have not copied more than 7 pages from Large Language Models (LLM).

Appendix A

Admin. “Tool Chest Buyers Guide: Which Tool Chest Do I Need?” *Help & Advice*, 29 Jan. 2024, www.sgs-engineering.com/help-advice/which-tool-chest-do-i-need.

“Bang Bang - BLRS.” BLRS Wiki, https://wiki.purduesigbots.com/software/control-algorithms/bang-bang. Accessed 9 March 2024.

Gomes, M. V., Bassora, L. A., Morandin, O., & Vivaldini, K. C. T. (2016). PID control applied on a line-follower AGV using a RGB camera. *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. https://doi.org/10.1109/itsc.2016.7795553

Gunn, Erik. “Smart Toolbox.” Municipal Sewer and Water, 31 Oct. 2017, www.mswmag.com/editorial/2012/04/smart_toolbox.

Heaven, W. D. (2023, April 7). *CHATGPT is going to change education, not destroy it*. MIT Technology Review. https://www.technologyreview.com/2023/04/06/1071059/chatgpt-change-not-destroy-education-openai/

HIX.AI. (2023, September 29). *10 CHATGPT Alternatives & Competitors (free and paid)*. PCWorld. https://www.pcworld.com/article/2086819/chatgpt-alternatives.html

Ina. (2023, July 26). *The history of Chatbots – from Eliza to chatgpt*. AI-chatbot software for complex requirements. https://onlim.com/en/the-history-of-chatbots/

“RFID Tool Management Equipment.” *RFID Smart Toolbox-Guangzhou Rovinj Mdt InfoTech Co., Ltd*, en.rovinj.cn/index.php?s=index%2Fshow%2Findex&id=212. Accessed 2 Feb. 2024.

Rossiter, J. A. (2013). *Model-based predictive control a practical approach*. CRC Press.

“Smart Tool Box.” *Tool Raptors Ltd*, www.toolraptors.co.uk/smart-tool-box. Accessed 2 Feb. 2024.

“Smart Tool Cabinet.” *Tramontina Global*, global.tramontina.com/en/pro/smart-tool-cabinet. Accessed 2 Feb. 2024.

“What Is Lamp Stack?” *IBM*, www.ibm.com/topics/lamp-stack. Accessed 1 Mar. 2024.

“What Is The Mern Stack? Introduction & Examples.” *MongoDB*, www.mongodb.com/mern-stack. Accessed 1 Mar. 2024.

“ESP32.” *ESP32 Wi-Fi & Bluetooth SoC | Espressif Systems*, www.espressif.com/en/products/socs/esp32. Accessed 2 Mar. 2024.

Raspberry Pi 4 Model B Specifications – Raspberry Pi, www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/. Accessed 2 Mar. 2024.

“Arduino® Uno R4 WIFI.” *Arduino Online Shop*, store-usa.arduino.cc/products/uno-r4-wifi?selectedStore=us. Accessed 2 Mar. 2024.

“PEP 8 – Style Guide for Python Code.” *Python Enhancement Proposals (PEPs)*, peps.python.org/pep-0008/. Accessed 4 Mar. 2024.

Yu, H. (2023). Reflection on whether chat GPT should be banned by academia from the perspective of education and teaching. *Frontiers in Psychology*, *14*. https://doi.org/10.3389/fpsyg.2023.1181712

“Oriented Strand Board as a Building Material”, Oklahoma State University, https://extension.okstate.edu/fact-sheets/oriented-strand-board-as-a-building-material.html. Accessed 16 Apr. 2024