Wrench Monkey - Streamlining Tool Retrieval and Return with a Mobile, Semi-Autonomous Toolbox

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***Abstract* — Wrench Monkey introduces a novel approach to increasing industrial efficiency with its semi-autonomous tool retrieval system. Designed to navigate factory floors autonomously using line tracks and equipped with advanced RFID and weight sensing technologies, it optimizes tool delivery to multiple workstations, minimizing downtime and human intervention. By streamlining tool management and distribution, Wrench Monkey enhances operational efficiency, freeing workers from constantly looking for tools to focus on important activities. This innovative system promises significant productivity gains in manufacturing environments by ensuring accurate and prompt tool delivery based on real-time needs.**

I. Introduction

For decades, robotics have transformed industries by automating tasks and enhancing efficiency, from precision manufacturing to logistics and assembly lines. However, the potential of robotics in shared workspaces, where collaboration and accessibility are critical, remains largely untapped. In such environments, efficient tool organization is paramount but often challenged by traditional manual tracking methods, especially as workspace complexity and personnel increase.

Our senior design project addresses these challenges head-on with robotics and automation, aiming to radically improve tool management in shared workspaces. Our solution, Wrench Monkey, is a semi-autonomous toolbox robot, which seeks not only to boost efficiency but also to redefine workplace dynamics. By integrating advanced technology into everyday tools, we aim to create adaptable, and technologically advanced workspaces that enhance productivity and user experience. The primary objective of our project is to increase workplace productivity and streamline tool management in shared workspaces. This system will address two main goals: tool transportation and tool organization.

For tool transportation, our first objective was to design and construct a robust frame capable of supporting a toolbox and integrating a drive system that enables autonomous navigation across the work environment. This includes selecting suitable treaded tires to navigate without requiring manual intervention.

Achieving semi-autonomy involves equipping Wrench Monkey with sensors to follow taped paths to designated workstations, marked with RFID tokens. Along with the RFID reader, an array of five infrared sensors is used in order to allow for accurate line following using PID controls. In addition, an ultrasonic sensor is mounted on the front of the chassis to provide object detection as a safety measure, so it will stop if it detects something in it's path. Using multiple different sensors will ensure accurate navigation, while detecting and alerting users to obstacles in its path.

In terms of tool organization, our objectives focus on improving accessibility and tracking. We implemented two different methods of tool detection. The first is a pressure sensing system within the drawer of the Wrench Monkey to detect tool presence, and the second is RFID readers also within the drawer, paired with RFID stickers on the handle of the different tools.. There is an integrated Wi-Fi module for real-time tool tracking via a web application. This allows users to request and track tools efficiently, ensuring they are available when needed and preventing movement to another workstation without the required tools. A lighting system highlights requested tools for quicker identification.

Wrench Monkey features several functionalities to meet our project goals. Users can call Wrench Monkey to specific workstations via a web app, which also notifies them which tools are available or unavailable. Its flexible design allows easy adaptation to different work environments by simply adjusting tape paths, supported by infrared and ultrasonic sensors for line following and obstacle avoidance.

Enhanced tool organization is facilitated through LEDs that highlight requested tools, aiding quick selection without unnecessary searching. The system logs tool usage and locations, making it easy for users to see who, where, and when a tool was checked out.

II. System Components

The system consists of multiple on-board and separate interconnected components which work in unison to achieve our project's goals. This section provides information for each of the critical components of Wrench Monkey.

A. Microcontroller

The ESP32 was chosen for Wrench Monkey due to its exceptional combination of features that cater perfectly to the project's needs. One of the primary reasons is its low cost, making it an economical choice for our budget-conscious project. The small form factor of the ESP32 is another critical advantage, allowing for easy integration onto a smaller PCB compared to other common MCUs. Additionally, the ESP32 boasts a plethora of GPIO pins, offering extensive connectivity options for the various sensors, motors, and other peripherals we implemented.. The support for multiple communication protocols, such as SPI, I2C, and UART, ensures seamless interaction with a wide range of external devices, further broadening its applicability.

Beyond these technical specifications, the ESP32 is also useful due to its 240MHz, dual-core processor, which enables faster performance in real-time applications. Its built-in Wi-Fi and Bluetooth capabilities provide robust wireless communication options, crucial for IoT projects like Wrench Monkey that require remote monitoring and control.

B. Radio Frequency Identification Readers

The 13.56 MHz RC522 RFID module was selected for tool detection and station detection in the Wrench Monkey project due to its numerous advantageous features. Primarily, its low cost makes it a budget-friendly option for our project. Its wide availability meant modules could be sourced easily, preventing problems caused by lead times. The module's easy integration with microcontrollers like the ESP32 simplified the development process, and reduced the overall time required for system design.

Additionally, the RC522 operates on low power, making it energy-efficient and suitable for our battery-operated application. Beyond this, the RC522's reliable performance in reading RFID tags ensured accurate and consistent tool recognition and station identification. Its compact design also allowed for easier incorporation into the tool chest drawer, as well as under the motorized chassis.

C. Strain Gauge

Thin film resistive strain gauges were chosen for simple tool detection in the Wrench Monkey project due to their affordability, thin profile, and ease of implementation with the ESP32. These gauges are inexpensive, making them a cost-effective solution for widespread application across multiple tools without significantly impacting the project budget, and allows future expansion. Their thin and flexible design allows them to be discreetly attached to various parts of the toolbox without adding unnecessary bulk.

Integration with the ESP32 MCU is straightforward, requiring only a single ADC input, simplifying the circuitry and reducing the complexity of the system. Additionally, thin film resistive strain gauges provide reliable and accurate measurements of strain, ensuring repeatable and reliable tool detection. They are also durable and resistant to environmental factors, such as temperature fluctuations and mechanical stress.

D. IR Sensors

The 5 IR sensor array was chosen for multiple reasons. Namely, the array is inexpensive, making it a practical choice for mass manufacturing without significantly increasing project costs. Its straightforward integration with MCUs simplified the design process, allowing for quick and efficient setup. The flexibility of the IR sensor array is particularly notable in its control applications. Initially, a bang-bang control scheme was implemented using just two sensors, providing basic line detection and control functionality.

However, the system's capabilities were later enhanced with the introduction of a PID control scheme utilizing all five sensors, offering more precise and responsive control. Additionally, the IR sensors' non-contact nature ensures durability and reliability, as they are less prone to wear and tear. Their ability to function effectively in various lighting conditions and environments further enhanced their utility in the Wrench Monkey project, ensuring consistent and accurate line detection.

E. Ultrasonic Sensor

The HC-SR04 ultrasonic distance sensor was selected for obstacle collision avoidance in the Wrench Monkey. This sensor is cost-effective, making it a suitable choice for maintaining a low budget while achieving reliable performance. Its straightforward integration with the ESP32 MCU and minimal circuitry allowed for quick development.

The small form factor of the HC-SR04 also ensured that it can be conveniently mounted on the front of the Wrench Monkey chassis without interfering with the toolbox, maintaining the system's sleek and functional design. The sensor's capability to accurately measure distances makes it ideal for detecting obstacles and preventing collisions. Additionally, the HC-SR04's robustness and ability to perform well in various environmental conditions contribute to its effectiveness in real-world applications. Its wide detection range and consistent performance further bolster its suitability for obstacle avoidance, ensuring the

Wrench Monkey can navigate its environment safely and efficiently.

F. Motors

Servo motors were chosen for the Wrench Monkey project due to their high torque, which was essential for moving the weight of the chassis, toolbox, and all other components. These motors provided the necessary power to ensure smooth and consistent movement, making them a critical component for the project's functionality. The high torque capabilities allowed the Wrench Monkey to handle the substantial load, maintaining stability and performance even when fully loaded with tools. Additionally, the servo motors were relatively easy to integrate with the ESP32 MCU, simplifying the control and operation of the system.

However, to ensure the motors were securely and rigidly attached to the chassis, a custom mount was required. This custom mount provided the necessary support and alignment, preventing any unwanted movement that could compromise the system's durability and otherwise cause the chassis to fail or the motor mounts to otherwise bend beyond repair.

G. H-Bridge

The L298P H-bridge was chosen for the Wrench Monkey project due to its small form factor, ease of control, and suitable maximum current rating. Its compact size made it an excellent fit for the small PCB design, ensuring that all components could be easily integrated without overcrowding. The ease of control provided by the L298P allowed for straightforward interfacing with the MCU, simplifying the implementation of motor control functions.

Its maximum current rating was sufficient to drive the motors used in the project, ensuring reliable performance under various load conditions. However, during operation, active thermal management was necessary to prevent the chip from overheating. This involved the use of a heatsink and a fan, which helped to dissipate heat and maintain safe operating temperatures for the chip.

H. Main PCB

The main control board consists of 5V and 3.3V switching regulators, the ESP32 MCU, and the H-bridge motor driver contained on the main PCB. The other peripherals, such as the RFID readers, ultrasonic sensor, and strain gauges are all connected to the main board via custom-made connecting cables. Copper ground planes were used for each side of the board to allow adequate return paths for the high-current motors. Because all sensors are placed on the chassis, while the main board is on top of the toolbox, extension cables were made in order for all peripherals to be connected to the main control PCB.

III. SYSTEM CONCEPT

The software system, which is responsible for tool management, tracking, and navigation is complex and comprehensive. Interfacing databases, webapps, and the hardware itself brings many challenges. The hardware system is also comprised of multiple components and subsystems that work in conjunction with one another to achieve the goals of our project.. All sensors and peripherals are integrated on both the hardware and software levels.

A. System Software Concept

The flowchart below outlines the main software control of Wrench Monkey, and the programmed response based on user requests.

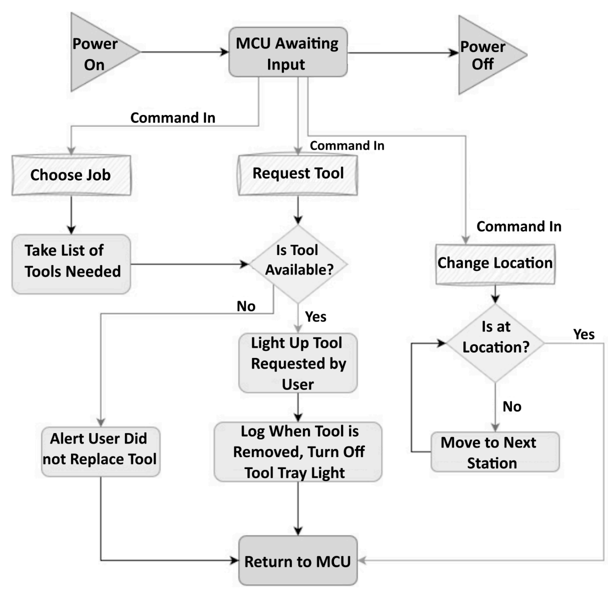


Fig. 1. System software flowchart outlining the main functionality and behavior of Wrench Monkey, based on user input and interaction

The software flowchart shown above shows how the programmed firmware operates step by step. Initially, the system starts in the "MCU Awaiting Input" state, ready to receive commands from the user, after successfully connecting to the webserver. When the user interacts with the system, it can proceed to either handling tool requests or changing station locations.

For tool requests, the system first checks if the tool is available. If the tool is available, it traverses to the desired station of the user who requested the tool. When the station the requesting user is at is reached, the toolbox drawer lights up the corresponding tool tray to indicate this to the user. The system then waits for the user to take the tool out of its respective slot. Once the tool is taken, the light turns off, and the system goes back to waiting for new commands. If the tool is not available, the system alerts the user that the tool cannot currently be checked out.

For location changes, when a user at a different station requests a tool, the system first checks if it is already at the requested location. If it is, the system checks out the tool and returns to waiting for the next command. If it is not, the system moves to the new location, lights up the requested tool in the drawer, and then goes back to waiting for new commands. During this whole process, the system makes sure that tools are properly managed and alerts the user visually on the toolbox drawer and webapp site. If any tool is not put back in its place. When changing locations, the system displays progress or status updates to keep the requesting user informed.

B. System Hardware Concept

The high level hardware block diagram is shown below, outlining the main components of our system, and how each is connected to the main control PCB.

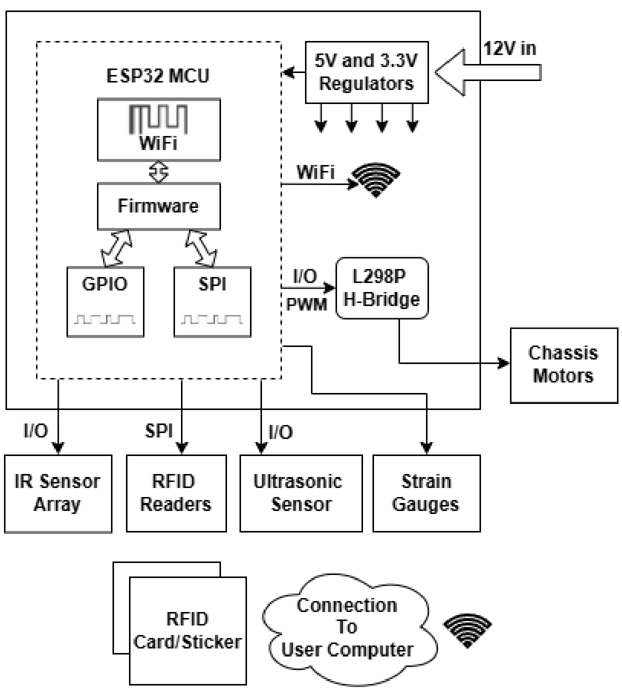


Fig. 2. Hardware block diagram showing main components of the Wrench Monkey system and main control PCB

The main digital communication protocol used is SPI, implemented with the RFID sensors for tool detection and station detection. All other components utilized the 24 available GPIO pins available on the ESP32 module we had chosen for use in Wrench Monkey.

IV. Website

A website was created and is available in order to access and utilize the Wrench Monkey toolbox. Each user will navigate to the url “wrenchmonkey.life”, and create their ownn personal account. They will then be able to use this account to request specific tools to their workstation. The website is equipped with two different types of accounts, an administrator account that is equipped with elevated permissions, and a user account equipped with normal permissions.

A. The Administrator Account

The administrator account is created automatically when the first user registers on the system. This account is unique and holds exclusive privileges, allowing the user to manage the tools within the database. One such privilege is the ability to introduce new tools to the database. If certain tools are no longer needed or relevant, the administrator can also remove them from the database. Additionally, the administrator can change the names of existing tools, which is useful for correcting errors, updating terminology, or making the tool names more descriptive and user-friendly.

B. The User Account

The normal user account has less permissions, and is solely used to operate the toolbox’s check in/out and station calling functions. It has the ability to call the toolbox to a specific workstation. It also allows users to check out a new tool, or check back in a previously borrowed tool.

When checking out a tool, a user should call the Wrench Monkey to their workstation, and then select the “check out” button on the tool they wish to use. The LEDs on the inside of the drawer will light up to highlight the location of the requested tool. If the LEDs are red, the tool is missing. If they are green, the tool is present and available. The previously green highlight of the tool name on the website will also turn red to signify that the tool has been checked out. To return a tool, select the “check in” button. The LEDs will again light up the tool’s slot in the drawer. The red light will signify that the tool is missing, and the green light will signify that the tool has been returned. For the tools that use the RFID reader in order to identify if they are present will also have the additional functionality of turning purple if the incorrect tool is placed in that position.

The website is also equipped with a “history” column in which it will record the tool that has been checked out, the time it was requested, the user that requested it, and the time it was checked back in if it has already been returned. This allows users to identify who had a tool last if it is missing.

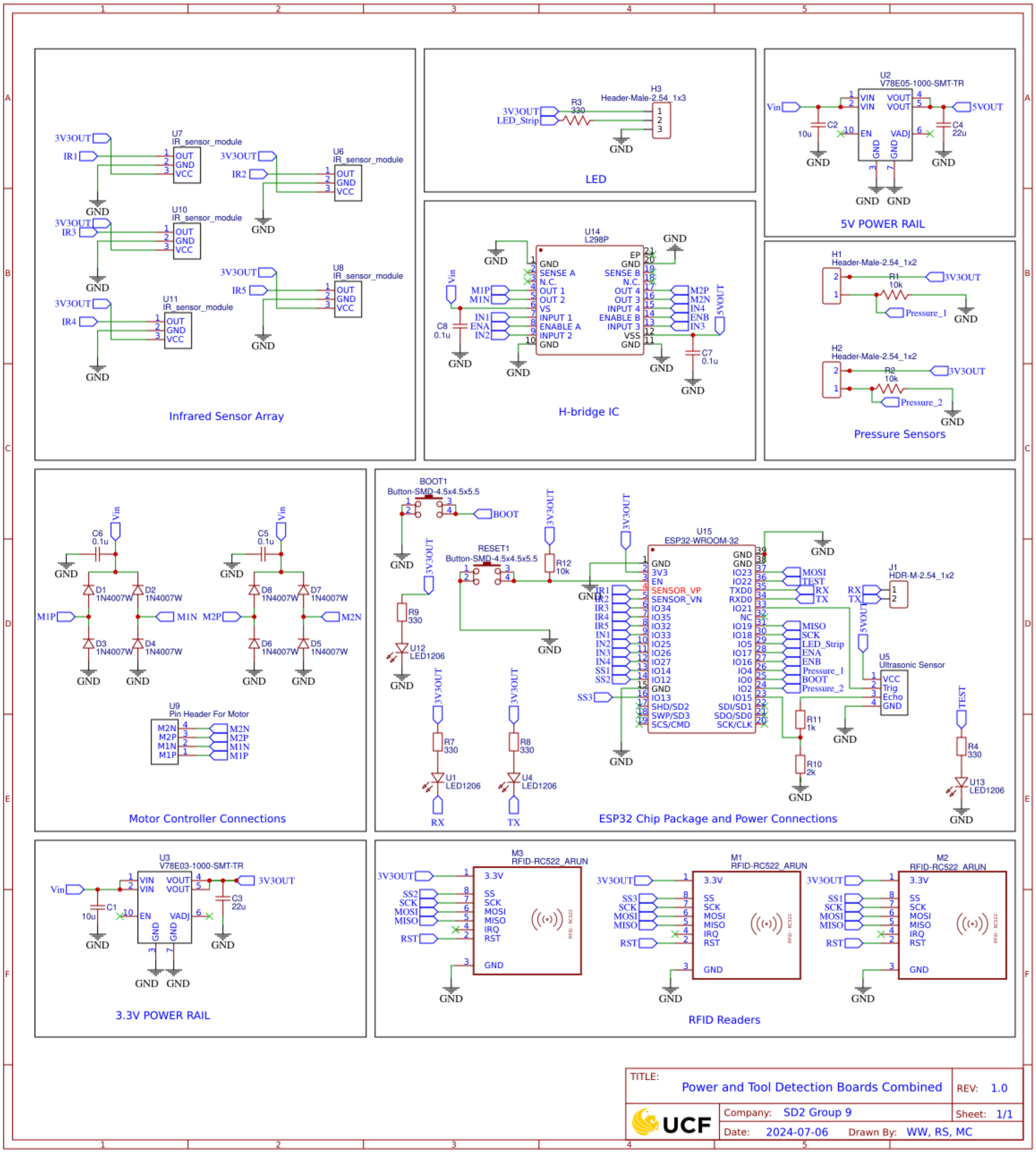


Fig. 3. Schematic showing the contents of the custom PCB created for the Wrench Monkey

V. PCB Design

This PCB Design was created using EasyEDA. The board was ordered unassembled and it, along with the stencil and the components, were ordered through JLCPCB. The PCB was then fully assembled in the UCF Senior Design Lab using the reflow oven. The PCB is made up of 9 smaller segments as shown in figure 3.

A. ESP32 Chip Package and Power Connections

This section of the PCB contains the ESP32 microcontroller and all of the connections. This section of the schematic also includes the ultrasonic sensor, which is used to detect objects in the path of the toolbox, which will cause it to stop moving. This is built in as a safety feature. This section also includes a boot and reset button used for programming, an LED to signify that the board is on as well as an LED to signify if the board is transmitting over UART, and header pins in place for the serial converter. The serial converter allows us to program the ESP32 while it is already soldered on the PCB. The transmit, receive, and ground pins on the serial converter connect to the receive, transmit, and ground pins on the ESP32.

B. RFID Readers

The RFID section of the PCB contains three sets of header pins for three separate RFID readers. Each RFID reader shares the MISO, MOSI, SCK, 3.3V, and RST pins, and they each have their own individual SS pin. The choice to use header is to allow us to place the PCB on the top of the toolbox, while placing two of the RFID readers within the drawer to act as tool detection sensors, and the third RFID reader is placed on the bottom of the chassis to detect if the toolbox has reached the correct workstation.

C. Motor Controller Connections

The motor controller connections section in the PCB schematic displays how the motor is hooked up to the PCB. This section consists of two flyback diodes and a set of header pins. The header pins allow the motors to be connected to the PCB to allow for PID controls to be possible. They are also labeled on the silk screen with the polarities to ensure that the motors will connect to the correct polarities each time. The flyback diodes are present to help prevent voltage spikes, which could burn out components on the PCB or the motors.

D. 3.3V Power Rail

The 3.3 volt section in the PCB schematic displays the 3.3 volt regulator that is incorporated in our project. This regulator is a switching regulator. It supplies power to the infrared sensor array, the LED strip, the RFID sensors, the pressure sensors, and the serial converter that is used when the ESP32 microcontroller is being programmed. It is equipped with filtering capacitors on both the input and the output of the regulator. The filtering capacitors help reduce AC noise, and they also help prevent sudden drops and spikes in voltage, which could ultimately damage the other components on the PCB.

E. Infrared Sensor Array

The infrared sensor array is connected to the PCB via header pins. The infrared sensor array is used for the line following function of this project. Header pins were chosen for this sensor as it allowed the sensors to be placed below the chassis, and run wires up the back to the PCB which is positioned on the top. A five sensor array was chosen to allow for PID controls to be implemented, which allows for smoother adjustments than would be possible using two IR sensors with Bang-Bang controls.

F. Pressure Sensors

The pressure sensors section of the schematic is simple, consisting of two sets of header pins for the two pressure sensors, and a 10 kilo ohm resistor for each sensor. The pressure sensors are connected via header pins as this allows them to be placed in the drawers, within the tool slots. They are used as a secondary method of tool detection, detecting if the tool is in the drawer by measuring the change in resistance when the tool is placed on top of the sensor, which places pressure on the sensor which causes the resistance to change.

G. 5V Power Rail

The 5 volt power rail, similar to the 3.3 volt power rail, is also present to help regulate and supply power to different components. It also is equipped with filtering capacitors on both the input and the output to help reduce AC noise and prevent rapid voltage spikes and drops, which could damage other components on the PCB. The 5 volt regulator helps to supply power to the motors.

H. LEDs

The LED section of this schematic includes a set of three header pins, as well as a resistor on the data line of the LED. The data line connects to a GPIO pin on the ESP32, and the other pins connect to ground and the 3.3V pin. The LED uses header pins as this allows the lights to be placed within the drawer, and the lights are used to light up the requested tool and display its status as present, missing, or incorrect tool.

I. H-Bridge IC

The H-Bridge IC section of this schematic displays how the H-Bridge is connected to the ESP32. The H-Bridge is an important part that helps control the motors, which allows us to use PID control to accomplish line following. The H-Bridge is used to enable, disable, and control the speed of the two motors that are being used, and takes in the Pulse Width Modulation (PWM) signal in order to control the movement of the toolbox. It uses 4 inputs and is able to switch the polarities of the motors as well in order to make turns. The H-Bridge utilizes flyback diodes to help prevent back EMF, which could easily burn out the H-Bridge, as well as the ESP32 microcontroller and other components on our PCB.

When creating and assembling our PCB, we also connected the current sensing pin to ground. This is because it was determined that we would not need to measure the exact current being used by the motor, and therefore that pin could be grounded as that would allow full functionality of the H-Bridge without adding extra components or requiring more GPIO pins to measure the current. In addition to this, a heat sink is also added on top of the H-Bridge, as without it, too much heat would be generated too quickly due to the motors enabling, disabling, and switching polarities to allow the toolbox to accurately line follow around a curve, quickly damaging the chip. An external 12V fan is also added, and faces the PCB, as this helps to quickly dissipate heat. This allows our H-Bridge to properly function even under extreme conditions of frequent, tight turns.

VI. 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.

A. 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.

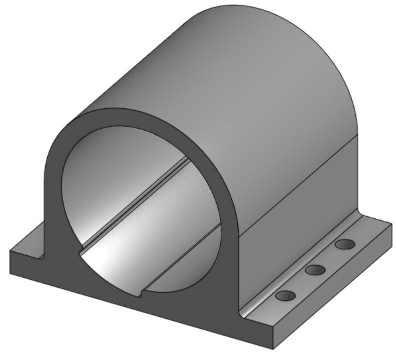


Fig. 4. Motor Mount to Chassis

B. 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.

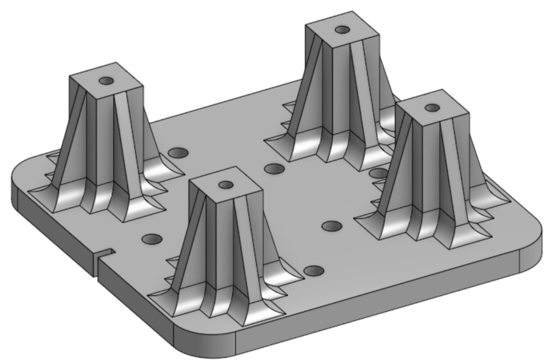


Fig. 5. RFID Mount to Chassis

C. 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.

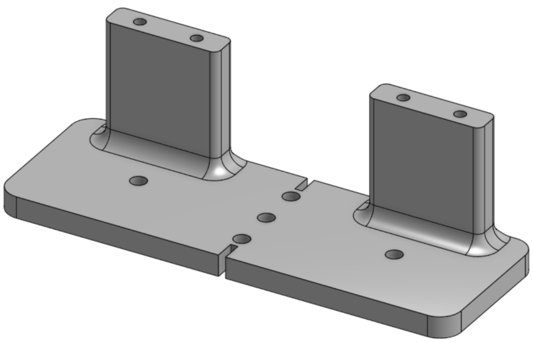


Fig. 6. IR Array Mount to Chassis

D. 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.

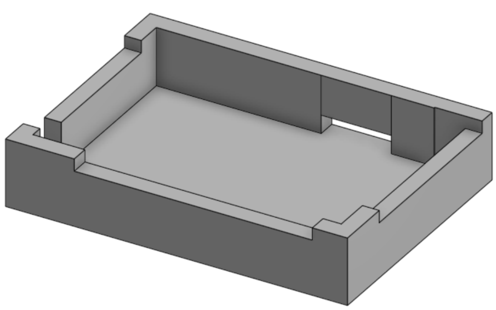
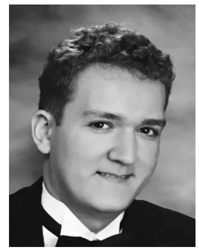


Fig. 7. PCB Enclosure Mount to Toolbox

VII. ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance and support of Dr. Lei Wei and Dr. Arthur Weeks. They would also like to thank Professor Mark Maddox, Dr. Aman Behal, and Dr. Mike Borowczak for being their reviewers for this project.

VIII. BIOGRAPHIES



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