ELECTRICAL AND COMPUTER ENGINEERING
COLORADO STATE UNIVERSITY

RamBOTs

Mid-project Report

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ABSTRACT

The RamBOTs senior design project, an extension of Electrical and Computer Engineering (ECE) Outreach, aims to contribute to outreach efforts of the ECE department by creating an educational tool tailored for diverse student age groups, from middle school to undergraduate college students. Within the robotics industry, quadrupedal robots, like the one our team is developing, face significant accessibility barriers, often being prohibitively expensive or exclusively available to companies with specific industry connections. Our project challenges these barriers by leveraging an open-source foundation—openDog V3 by James Bruton [1]—to produce and document a more affordable and accessible version of a quadrupedal robot. This will make it openly available and serve as an effective educational tool for students with varying technical backgrounds and across different age groups.

The core of our project centers on the enhancement of the open-source foundation. Despite its availability, openDog V3 lacks comprehensive software documentation and presents opportunities for overall improvement. Our team has tackled these shortcomings by elevating the documentation standards of this open-source project and implementing modifications where needed. Notable progress includes updating documentation from previous years, refreshing components that have experienced wear over the years, and enhancing the ODrive interface to improve walking movements. Moreover, the team has developed a fifth leg as a dedicated testbench to streamline the debugging process, particularly for motors. This allows for more precise and efficient testing, as well as improving troubleshooting procedures.

Our project's key findings underscore the critical importance of comprehensive documentation and thorough testing. Unit testing, conducted on the dedicated testbench, prioritizes the device's safety and promotes repeatability in the testing process. Now in its third year, this project is an ongoing mission to transform the robot into a reliable and effective educational resource. Consequently, areas for further development include the refinement of balance and walking movements, incorporation of the existing machine-learning model for object tracking, and the establishment of pre-programmed movement sequences.

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Chapter 1. Introduction

1.1 Project Overview

Quadrupedal robots, representing a recent innovation in the robotics industry, currently serve diverse roles, from rescue missions to construction site surveying. As this technology is still in its early stages, with continuous exploration of new applications, these robots remain largely exclusive and are primarily accessible to established companies, making them inaccessible to individuals. The substantial cost associated with these robots places them beyond the financial reach of the average person. The overarching objective of this project is to dismantle these accessibility barriers within the robotics industry. This is achieved by developing an open-source and cost-effective alternative to quadrupedal robots, thereby significantly enhancing accessibility to this transformative technology.

This project is built upon the open-source framework of openDog V3 by James Bruton, with significant enhancements to align with its accessibility goal. The foundation comprises entirely 3D printed components, a strategic choice to reduce the overall production cost of the robot. In addition to its plastic chassis, the robot incorporates twelve brushless motors, six ODESCs (motor controllers), one DualShock 4 controller, one Teensy 4.1, and one Raspberry Pi 4B. The Raspberry Pi plays a crucial role by managing the multithreading intricacies of the project, allowing it to concurrently handle various forms of input and data. The information collected by the Raspberry Pi is then transmitted to the Teensy. This microcontroller works directly with the motor controllers, ensuring precise motor movements in response to input received from the DualShock 4 controller, which serves as the primary interface for controlling the robot. The integration of these components not only enhances the robot's functionality but also contributes to the project's broader goal of making quadrupedal robots more accessible and affordable. Through comprehensive public-facing documentation of this project available on our GitHub [2] repository, the robot serves not only as a guide for individuals interested in robotics but also as a valuable educational tool.

1.2 ECE Outreach

The RamBOTs project, as an extension of ECE Outreach, aligns with the primary goal of enhancing recruitment and retention within the ECE department and the broader CSU engineering college. The team actively participates in events and workshops aimed at showcasing the opportunities within the field. Throughout the semester, the team participated in events such as the Engineering Takeover Event and STEM at Homecoming. During these occasions, team members showcased the robot, fielded questions about the project, and shared insights about their chosen degrees. These endeavors played a crucial role in offering both potential and current students valuable insights into the diverse opportunities available within the ECE department at CSU. The final product, even when in a nonfunctional state, serves as a valuable educational tool at outreach-based events, illustrating engineering concepts such as power, interdisciplinary collaboration, mechanics/kinematics, machine learning, CAD, and robotics.

1.3 Objectives and Design Requirements

The RamBOTs project is driven by a set of objectives, distinguished into short-term and long-term goals. Short-term goals were to be completed by the end of this first semester while long-term goals are projected to be completed by E-Days. For the short term, our focus revolved around four key objectives: (1) developing a fifth leg model to conduct simulation and stress testing of the legs; (2) fine-tuning the robot's walking movements and overall balance; (3) implementing comprehensive safety updates for the well-being of the team and individuals during outreach events; and (4) updating documentation and creating how-tos to ensure seamless information sharing across our extensive team. For the first goal, specific design requirements dictated that the 5th leg stand must perform and record both kinematic and load testing, allowing for code changes before application to the robot. Regarding the second goal, the design requirement stipulated that the robot should stand and walk for the duration of an outreach event, approximately 1 hour. Safety considerations for the third goal included the robot stopping if there is an object within a 1-foot perimeter, ensuring the batteries continuously output no less than 21V for 30 minutes in use to avoid overheating and associated risks, and finally designing 3D printed parts within tolerance for proper fit and structural integrity with 40% cubic infill for the majority of parts. As we progressed through the semester, our project's goals and design requirements evolved, adapting to unforeseen challenges. Despite initial setbacks, the team made progress in all these categories, elaborated upon in the subsequent sections of this report.

Looking ahead, our team envisions several long-term goals for E-Days. We aim for the robot to track and follow a ball, optimize the walking sequence, and enhance bystander engagement through interactive features. To accomplish these goals, the proposed design requirements require the robot to recognize objects consistently (75% of the time), walk on a flat surface with no need for external support for its entire operation time, and respond to controller input within a response time of 100ms. With the design requirements in mind, the mechanical engineering team plans to create several simulation models, including SolidWorks and Abaqus Finite Element Analysis (FEA) models, and run simulation analysis to assess and optimize the structural integrity and performance of the robot's components. Simultaneously, the electrical engineering team will be dedicated to producing comprehensive documentation, safety reviews, and complete schematic diagrams to facilitate a seamless transition for the succeeding project team. The computer engineering team will ensure the safety of bystanders and the robot by using obstacle detection. It is important to note that obstacle detection is not intended to be used for navigation purposes. The software's primary goal is to successfully follow a specified 'fetching' object, with the retrieval not initially planned due to inherent mechanical complexities. Lastly, by E-Days, every team member should be capable of proficiently explaining the major aspects of the robot, covering mechanical systems, electronic integrations, the software stack, and the overall synergy of the entire system.

1.4 Organization of the Report

The remainder of this report consists of six separate pieces. Chapter 2 includes a summary of the previous work that was completed by the two previous senior design teams and given to the current team. Chapter 3 covers the improvements made to documentation and the hardware including a discussion on what parts had to be modified, replaced, and redesigned, as well as the power distribution and wiring for the robot. Chapter 4 discusses the software aspects of the project and provides a general overview of the progress on obstacle avoidance followed by an in-depth explanation of interface updates made for the ODESCs. Chapter 5 focuses on the rationale for and the production and setup of the 5th leg testbench. Chapter 6 provides insights into the standards that guided the project such as safety, reproducibility, and documentation. In addition, it takes a look at the tools used throughout the semester. Chapter 7 is the conclusion of the report that summarizes the project in its entirety and Chapter 8 details the expected future work for the project as we transition to the next semester.

Chapter 2. Summary of Previous Work

RamBOTs is a multigenerational robotics project now in its third year as a senior design option. As such, there has been a great deal of progress made over the past two years to get it to its walking state.

The first-year team's efforts were mainly focused on acquiring the necessary hardware and developing software that was independent of hardware implementation. The first year's team faced significant challenges, primarily centered around acquiring materials, especially due to supply chain issues. Despite the difficulties, they successfully secured the necessary hardware and electronics, saving the second-year team valuable time. Another hurdle involved the extensive 3D printing required for the chassis, demanding large printers and significant time and cost investments. The first-year team also assembled the motor housings and gearboxes, including the intricate process of cutting metal rods and fitting them with bearings. Notably, they implemented object detection using machine learning, utilizing a fine-tuned MobileNet V2 model on a Raspberry Pi, complemented by a Google Coral hardware accelerator for improved performance. This robust foundation laid by the first team contributed significantly to the advancements achieved in the RamBOT project during the second year.

The second-year team successfully met expectations by transforming a project with untested hardware, a disconnected 3D-printed chassis, and an isolated machine-learning model into a fully functional and versatile quadruped robot. They addressed initial challenges, such as the absence of wired connections for the 3D-printed chassis and the disconnected machine-learning model. The team effectively integrated critical components, including Raspberry Pi, Teensy, ODESC motor drivers, and various sensors, creating a versatile and expandable robotics platform. Leveraging James Bruton's openDogV3 project as a foundation, they expanded open source robot's capabilities by incorporating Raspberry Pi, machine learning, gyroscope integration, and multiple modes of operation. Key achievements include the development of a software flow capable of managing high-level inputs, performing inverse kinematic calculations, and controlling the robot in various modes. Safety enhancements were prioritized, with the incorporation of breakers linked to both batteries, an emergency stop button, and safety switches to promptly address potential faults or malfunctions. Overcoming challenges like troubleshooting defective motor drivers, understanding complex firmware, and relocating their lab space; the team successfully produced a functional quadruped robot capable of diverse movements. The RamBOTs team showcased their achievements with a fully functional walking robot on the day of E-Days.

Despite the successes of the previous year's team, the transition period posed significant challenges for the third generation team. Upon commencing work at the beginning of the semester, it was discovered that the robot was no longer capable of walking and exhibited signs of leg weakness. During startup, the back legs were out of the closed loop and lacked the necessary rigidity to support the robot's weight. Additionally, the back-left shoulder motor vibrates back and forth, indicating potential issues both mechanically and structurally. These weaknesses were attributed to the rushed ODESC, motor, and encoder configurations performed by the previous year's team in the final weeks of preparation for E-Days. Furthermore, upon receiving the robot, the hardware and components showed signs of wear and tear due to the project being over a year old. This included worn-down and cracked 3D-printed parts and stripped screws. These issues were exacerbated by the quick fixes implemented by the previous year's team in the final week before E-Days. Glues and thin plastic spacers were integrated into the machinery, unable to withstand the pressures and heat generated during the robot's operation and melting in the process. These small system issues culminated in a systematic failure, rendering the robot incapable of walking as it had on E-Days the previous year. This provided a less-than-ideal foundation to begin the semester and prompted adjustments to our initial plans for future work on the robot.

Despite these setbacks, we made progress in addressing the robot's walking sequence, updating worn parts, and enhancing documentation to facilitate easy troubleshooting in the future. The details of our progress in these respective areas will be explored more comprehensively in the following sections of this paper.

Chapter 3. Documentation and Hardware Improvements

3.1 Addressing Poor Documentation

This semester, our team dedicated significant effort to addressing the issue of inadequate documentation inherited from the previous year's team. We identified a clear gap and lack of comprehensive documentation regarding crucial aspects of the project, such as the version of the Raspberry Pi used, the deployed machine learning model, and issues and difficulties encountered by the previous team. This information was scattered across multiple reports, requiring compilation into a single, easily accessible location. Moreover, key details about progress and design choices were often undocumented. For instance, the ODESC configuration was provided without explanations for certain parameter choices. Consequently, we had to seek clarification from the previous team on essential tasks, underscoring the need for improved documentation. This hindered our team's goals of enhancing the robot beyond the previous year's implementations and making it an easily accessible and intuitive open-source project for others. To enhance accessibility and self-sufficiency, our team revamped existing documentation and created instructional guides for basic tasks. The objective was to empower every team member, regardless of specialization, to perform tasks independently. Additionally, we undertook the task of updating schematics and wiring diagrams to showcase our team's professional development, improve clarity, and assist future teams in understanding the foundational aspects of the robot.

Given that one of our project's key priorities is to represent the robot clearly and professionally as part of ECE outreach, we observed that the previous team had created several brief documents and schematics not up to these standards. To tackle these concerns, we initiated updates to previous documents and schematics. For example, we updated the controller schematics for clarity. The previous team's chart had limitations, like incomplete mappings and ambiguous labels. Our detailed schematics focus on actions such as walking and providing clear instructions for each button. Similar schematics of the controller cover startup, pushups, leg control, dancing, gyro, and overall controls. These changes improve accessibility and ease of use. Another significant improvement involved the development and refinement of the wiring schematics inherited from the previous year's teams, exemplified by the complete

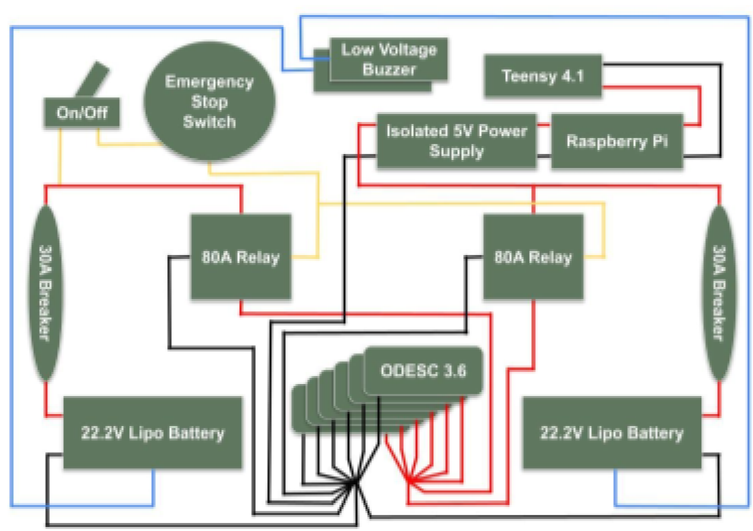

Figure 1: Initial Wiring Schematic Inherited from the Previous Year's Team

circuit diagram showcased in Figure 1. This schematic provides a fundamental overview of the wiring connections between key components, such as the ODESC, Raspberry Pi, Teensy, and the power supply. While it serves well for grasping the basic connections and understanding the control hierarchy, it falls short when it comes to offering a precise mapping between components. In essence, it lacks the granularity needed for tasks like re-wiring components that have been disassembled or integrating new components into the existing setup. To overcome this limitation, our team took the initiative to craft a new and more detailed schematic (Figure 2). This comprehensive diagram encompasses all the pin mappings and wire connections between components. It follows an organized structure, elucidating every pin and wire mapping, and employs engineering standard symbols for components like the on/off switch and the voltage supply. This upgraded schematic not only serves as a valuable reference for recreating connections accurately but also proves instrumental in the debugging process, particularly when identifying errors in the connections. Moreover, it enhances basic documentation, providing a thorough and accessible resource for understanding the intricacies of the wiring setup. Through this process of documentation, the electrical engineering team was better able to understand the setup of the robot, knowledge which aided them in the development and wiring of the fifth leg.

In tandem with our documentation updates, our team took a proactive approach to knowledge-sharing by creating a series of instructional how-to guides. Throughout the semester, whenever we encountered novel challenges or obstacles, we systematically documented the problem-solving processes employed. This valuable knowledge was then distilled into a collection of how-tos, ensuring that other team members or future project teams could efficiently address similar issues by referencing these comprehensive guides. The how-tos cover a range of topics, including disassembling and removing a leg, reflashing an ODESC, reconfiguring a motor and encoder, and repositioning the leg during startup. Many of these instructional guides emerged as a direct response to significant challenges faced early in the semester, particularly those associated with the walking sequence—issues that will be explored later in the paper. Issues with ODESC, motor, and encoder configurations posed substantial hurdles, and our team's documented solutions, crafted through trial and error, now serve as a streamlined and efficient resource for addressing such challenges in the future. This initiative aligns with our commitment to enhancing accessibility and ease of use, fostering a knowledge-sharing culture within the team, and leaving a valuable legacy for subsequent project teams.

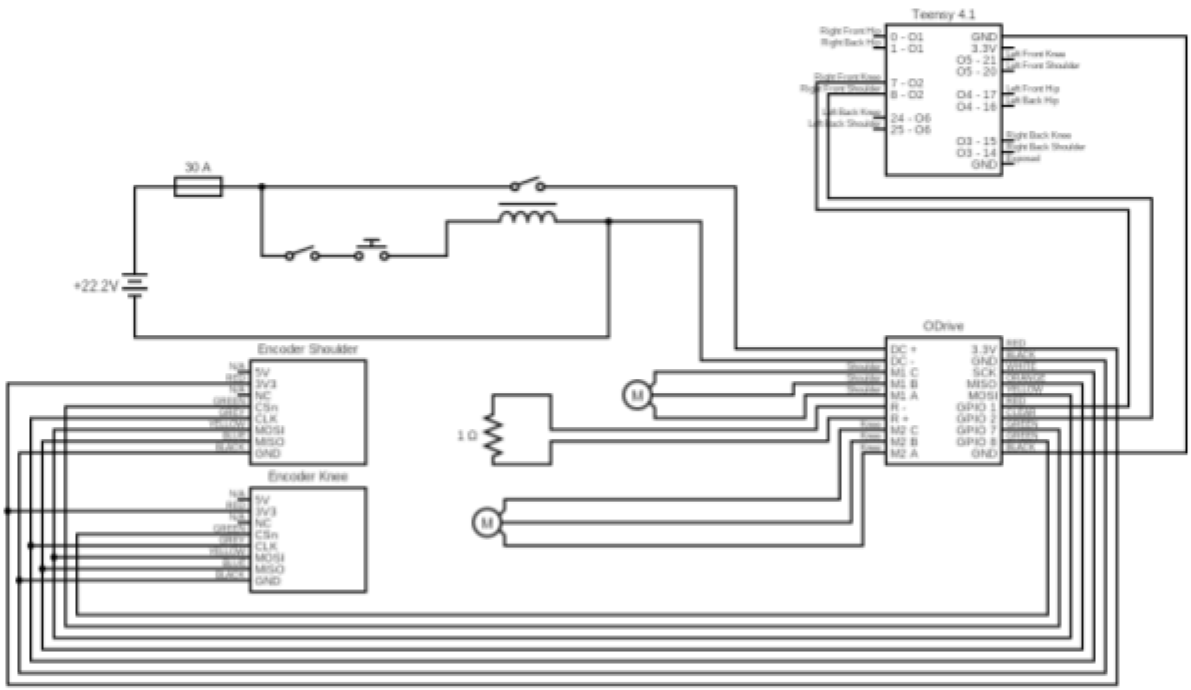

Figure 2: Enhanced Detail Schematic

3.2 Safety Improvement of Wiring and Battery Access

The safety of the robot and the team is paramount for the project's success. When we inherited the project, we found several concerning factors regarding the wires on the robot and the batteries. There were exposed wire conductors, and wires would randomly disconnect causing the robot to lose control. Additionally, the batteries were very difficult to access when the robot was on the stand. The team decided to allocate a few individuals to work on fixing these issues to increase the safety of the project significantly.

To achieve increased safety, we first focused on fixing all the exposed wiring. The black ground wire connecting the rear battery of the robot to the common ground of the whole system had a long slice through its insulation which exposed many of the inside wires. We were not able to identify the cause of the compromised wire, but we verified that the inside wires were not cut. We temporarily fixed this wire by wrapping electrical tape around it. Another area that was concerning was exposed wire between the battery wires and their connectors. The batteries are capable of producing a large current when the robot is in operation, and having their wires exposed raises the risks of fire and other harm if any conducting material falls on and shorts the exposed wires. We fixed these connectors by first covering the exposed wire with electrical tape, and then further isolating the wires from each other by using a hot glue gun at the base of the connectors. The hot glue gun was also used so the wires could not bend and re-expose themselves to each other, and then the team used more electrical tape to wrap around the wires and the connectors to ensure complete discontinuity between the wires and the environment.

Another problem with the wires were loose connections and faulty solder joints. These issues were random and challenging to troubleshoot. The team worked on finding visibly disconnected wires and loose solder joints to fix and repair. The team also performed continuity tests with a handheld multimeter to debug probable issues for why there was a loss of connection between the Teensy and ODESCs. The connectors between the Teensy and ODESCs have been found to cause the most issues as they easily become disconnected. The team has identified the possible causes for these disconnections and the plan to fix these issues is by implementing strain relief which will be discussed in Chapter 8.

The lithium polymer (LiPo) batteries on the robot are powerful but they also come with inherent safety concerns. The team at the beginning of the year discovered that it was challenging to remove the batteries from the chassis when the robot was on the stand; the robot had to be partially lifted off the stand to allow room for the batteries to be removed. Not being able to access the batteries quickly and efficiently would pose safety risks in a worst case scenario of a battery fire, and in the best case scenario could prompt carelessness with taking care of the batteries. To resolve this issue, the team modified the stand. We decided to elevate the robot higher on the stand to allow the battery doors to swing open far enough to allow the batteries to fit through. The new stand design means that only one person is needed to remove the batteries quickly when at least two people were previously needed.

3.3 Updating and Upgrading 3D Printed Components

3D printed parts are some of the most prevalent and important components of both the RamBOT and the single-leg stand, but we found early on that several of them were left quite worn from last year due to constant use. These failed parts made the RamBOT unable to function properly and helped inspire the creation of the single-leg test stand that will be used to perform coding, kinematic, and load testing. A majority of the structural parts of the frame and legs as well as the internal gears were printed parts made of PLA, and while these structural/external parts remained in good shape the same could not be said for the gears. See Figure 3 below for an example of the state of one of these gears. A significant amount of time and effort throughout the semester went into disassembling each preexisting leg to remove and replace worn parts, which mainly consisted of these internal 3D-printed components. It was clear that the material and infill of these parts desperately needed to be adjusted to prevent future failures. To fix this issue, finite element analyses, empirical tests, and numerous other approaches were considered and conducted. Many of these approaches were also conducted concurrently with testing and material application searching for the fifth leg and the testbench, whose own sections go into more detail on the testing and the results.

Figure 3: Worn 3D Printed Gear from Previous Years

For all parts that needed to be printed to replace those that have failed or completely new parts expected to undergo stress, the infill settings chosen were 40% cubic infill. For a few parts, notably the gears because they failed the most frequently and suffered the most wear, we decided that the PLA/PETG material that was being used for them needed to be changed. The new materials chosen to be experimented with were Nylon and HIPS, and the RamBOT's gears have now been replaced with Nylon counterparts. For more information on why these infill settings and new gear materials were chosen, see Section 5.2.

A critical component of the RamBOT is the stand; not only does the RamBOT rest on it when it is not in use, but the stand helps to calibrate the robot to achieve activation. The software controlling the RamBOT's motors needs to know exactly the position and location of the associated physical part to successfully perform movement, such as walking, without coming out of alignment. As a result of this, each motor and linked part within the RamBOT need to be in a specified position when the RamBOT is activated; to achieve this calibration, sections of the stand were specially designed and printed for this by the team last year. However, some improvements could be made by redesigning those components. The changes made to them include separating one static part into an assembly of three different components, allowing the new versions to fold into the stand when not necessary, to avoid being damaged by motor malfunctions or other mishaps. Another change was made to change the overall shape of the component that connected to the RamBOT to hold the 'legs' in place; previously, the silicone 'feet' rested on a small amount of material, relying on friction to hold the 'foot' in place. The new version instead has a hemispherical socket that the 'foot' can rest in, securing it in place more accurately and reliably. Similarly, other components of the stand were modified and reprinted to fit the needs of this year's team, eg. increasing the space between the center rail of the stand and the bottom of the battery enclosure to more easily work within that area.

Another part that needed to be adjusted was one referred to as the leg mounting part, which attaches a leg to the rest of the RamBOT. This is done with two similar (yet slightly different) parts that connect the leg to the robot's torso in a way that allows the motor within it to move the leg horizontally, perpendicular to the direction of the other two motors in the leg. These parts were left alone on the RamBOT, however, they needed to be changed to attach the single leg to its respective stand and hold it perpendicular to the ground, rather than allowing that horizontal motion described earlier. To do this, the simpler version of the part with a circular hole through the middle was chosen to be adjusted and used on both sides of the single leg rather than just one. The adjustment made was also quite simple, as the circular hole was changed to a square that is just large enough for the aluminum bars that we have been using for the single-leg stand to slide into. This new version of an older part has been working great so far, and is still being used in the single-leg test stand to support the leg.

Throughout the semester, several newly designed and 3D-printed parts were required to help achieve our goals. A few examples are the LiDAR mount that connects the LiDAR to the top of the RamBOT, as well as several parts for the single-leg stand that attach/secure the leg to the aluminum bars that run along the table or act as the supports and connection points for the triangular structure of the loading method. The loading method is still a work in progress, but all of the parts required to form the triangular shape have been designed and are ready to print if they have not been already. At the moment the plan for the loading method is to design and print a part that attaches the loading plate and slides along the vertical aluminum bar, as well as a part that prevents said loading plate from going all the way down with the leg during its walk cycle. This part will prevent the weight from crushing the single leg if too much load is applied, and it will also mimic the leg's expected walk cycle since the leg would lift off of the ground while walking if it were attached to the RamBOT.

Chapter 4. Software Improvements

4.1 Updates to ODESC, Encoder, and Motor Interface

In order to control each of the 12 motors on the RamBOT, 6 ODESCs are used. ODESCs are microcontrollers that receive higher-level movement commands from the Teensy and translate them into exact, per-motor movements. Naturally, in order to give precise and accurate commands to the motors, each ODESC must know where both of its corresponding motors are currently located. This is accomplished using relative encoders, specifically AMS AS5047P Magnetic Rotary Position Sensors. These encoders work by reading the magnetic field of a cylindrical magnet attached to and rotating with the motor. The magnets are polarized along the vertical axis of the cylinder, as shown in Figure 4. As the magnets rotate with the rotation of the motors, the encoders read the number of rotations and, if the ODESCs are calibrated correctly, can then give exact positioning data. These encoders can only read the number of rotations, not the starting position of the motors, which makes startup positioning absolutely vital. This was another large area of improvement for the RamBOT, which will be talked about in Section 4.2 below.

ODESCs and encoders are absolutely vital for motor operation on the RamBOT. All devices must be working properly and in synchrony to let the robot function at its best. However, at the start of the semester, this was not the case. ODESCs 3 and 6, which are responsible for the shoulder and knee joints of the back right and left legs respectively, were not working correctly. Neither of the RamBOT's two back knees would enter closed loop, the state where the motor is able to move and is holding its position. Closed loop motor operation is vital for the RamBOT's operation because when motors are in open loop they do not hold their position and cannot hold the robot up. At first, it was unclear if this issue was actually caused by the ODESCs or simply by improper positioning of the legs on startup, but after many startup attempts it became clear something larger was going wrong.

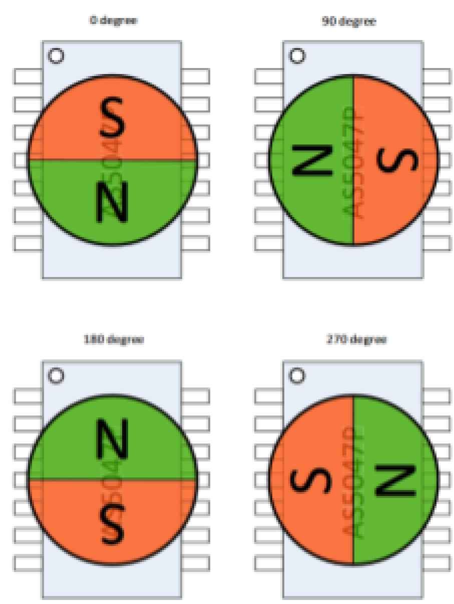

Figure 4: Magnetic Polarization (Source: [6])

The first step in the troubleshooting process was to connect to the ODESCs. This was accomplished by using the odrivetool software, which allowed a read of all errors being thrown by each ODESC. It was discovered that axis 0 on ODESC 6 was throwing errors consistent with the encoder being incorrectly calibrated. Axis 0 on ODESC 3 was also throwing errors, but they were unknown at this point in the process.

At this point, present and cohesive documentation would have saved the team many hours of work. Because there was no documentation on how to correctly calibrate an encoder, the team simply ran the encoder calibration script found in the RamBOTs testing repository on GitHub. However, what the team failed to realize was that the entire leg needed to be taken apart to allow the motors to spin freely without any load before the calibration script was run, and also that the calibration script was incomplete and needed major reworking, including adding a section to actually calibrate the encoders. The team also erroneously ran the incomplete script on ODESC 3 before finding the true cause of the errors, which later necessitated a complete recalibration process for both back legs.

During this process, the team discovered that ODESC 3 was throwing errors consistent with there being a missing wire connection. After some continuity testing, it was discovered that a solder joint on one of the encoders was undone. It was also discovered that the encoder connections were prone to coming unplugged where they plug into the ODESC wiring. The team fixed the solder joint and taped the plugs together as a preliminary fix before they could look into implementing strain relief.

After more research, the team figured out the correct calibration process and rewrote the script accordingly. The team added initialization steps to the script and added a section to actually calibrate the correct encoder. The final encoder calibration process is as so: take the correct leg apart to remove all load on the motor being calibrated, but do not remove the encoder plate from the assembly. Connect to the ODESC, and run the corrected calibration script found in the ConfigurationForODrives repository on GitHub. Wait for the motors and encoders to finish calibrating, then disconnect from the ODESC and reassemble the leg.

After recalibrating each encoder on both ODESCs, the team put both back legs together and discovered that the issues on both ODESCs were fixed. The team then wrote a How-To document detailing the process for recalibrating an encoder, to prevent future teams from making the same mistakes. This documentation effort after troubleshooting exemplifies this team's commitment to better, more reliable, and more organized documentation for the RamBOT.

4.2 Updates to Startup Leg Positioning

As mentioned in the previous section, the RamBOT's intricate motor control system relies on ODESCs to manage all 12 motors. Each motor connects to an ODESC, utilizing motor encoders for precise position determination. ODESCs enable setting motor positions by index with remarkable precision. With each ODESC capable of operating two motors, six ODESCs are strategically employed in the RamBOT design. Communication between ODESCs and the Teensy 4.1 occurs through hardware serial pins, with eight pairs available on the Teensy. Two sets remain unused, providing scalability for future expansions.

During startup, the Teensy initiates communication with the ODESCs by initializing serial objects (serial_1 to serial_6) at a baud rate of 115200. This preserves the 9600 baud rate for communication with the Raspberry Pi. Subsequently, ODrive objects from the ODriveArduino library are instantiated, facilitating direct control over the ODESCs. Velocity and current limits are established, followed by a restart and index-finding command for the ODESCs. The motors then execute a gradual clockwise motion until each locates its index. Upon successful index identification, the ODESCs transition to a closed-loop state, mitigating undesired movements. The system is now poised to receive precise motor movement commands, showcasing the efficiency and refined control architecture of the RamBOT. It is crucial to emphasize that the startup sequence holds paramount importance in ensuring the optimal functioning of the motors. Upon reaching the desired index, the motors transition into a closed-loop state, gaining the necessary rigidity to bear weight. As a result, the specific index to which the motors are calibrated becomes pivotal in determining the success of the walking sequence, influencing the physical dynamics of the robot's movements. Setting indexes at excessively obtuse angles hinders the utilization of the knee for stepping movements, while overly acute angles impede walking as the robot lacks sufficient space to lift its legs effectively. The careful calibration of these indexes is essential for achieving the desired and efficient locomotion of the robot.

Consequently, a pivotal factor contributing to our team's success in restoring the robot's walking functionality involved a significant improvement in the method for adjusting and calibrating the startup leg indexes. Throughout the semester, we improved a Python script that facilitates real-time modification of offset positions through intuitive and human-readable prompts. In contrast to the previous script, which required altering an extensive list of float values and restarting the robot each time, the updated approach simplifies the process. Now, users only need to select the desired joint and specify whether it should move forward or backward. They are then able to see the adjustments in real-time without having to first restart the robot, an arduous process to visualize a simple change. This enhancement not only streamlines the testing phase but also enhances user-friendliness by eliminating the need for manually adjusting numerical parameters. The revised script enhances accessibility and facilitates rapid adjustments during startup, offering a dynamic solution for tailoring leg positions to specific requirements. For instance, if one aims to modify the robot's standing position during startup, this procedure enables effortless adjustments until the legs assume the desired posture. Similarly, users can redefine the initial leg positions, ensuring seamless adaptation to different scenarios. This user-friendly and dynamic approach underscores our commitment to optimizing the operational efficiency and flexibility of the robot.

4.3 Obstacle Avoidance with LiDAR

The team has made progress on obstacle detection for the RamBOT using a Slamtec RPLIDAR A1, a highly reliable 360 Laser Range Scanner. This LiDAR was selected due to its ability to provide accurate and real-time distance measurements over a full 360-degree field of view. The team developed custom code to interface with the LiDAR, receiving angle and distance data to generate a 2D area map. This data was recorded in a CSV file for analysis and playback. A snapshot of this playback is shown in Figure 5, showing the successful mapping and recording of the environment as the robot is guided through the halls of the engineering building. A map showing the RamBOTs location in the engineering building at the time the LiDAR image was generated is included in Figure 6 shown below for comparison.

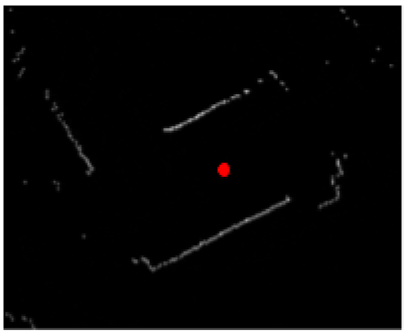

Figure 5: 2D Map Generated by LiDAR during Experiment

Figure 6: LiDAR Location Superimposed on ECE Building Floor Map

In addition to the mapping capabilities, the team engineered a script for seamless integration of the LiDAR data with the robot's controller. The inclusion of multiprocessing techniques optimized the efficiency of data processing, minimizing latency in mapping the LiDAR data to the controller. This integration ensures that the robot can respond dynamically to the environmental data, paving the way for future obstacle avoidance. Furthermore, the team initiated the implementation of a machine learning model with the objective of enabling the robot to learn optimal controller commands based on the 2D map data.

Moving forward, the machine learning model will be tested on the RamBOT to validate its ability to guide the robot effectively along a predefined path. Additionally, the LiDAR data will be leveraged for safety purposes, implementing a shutdown mechanism to halt the robot in the case that a person or object gets too close during operation. Furthermore, the team aims to refine the machine learning model for obstacle avoidance when walking. These advancements are a step towards an adaptive robot capable of navigating diverse and dynamic environments.

Chapter 5. Fifth Leg Testbench

5.1 Rationale for a Separate Testing Leg

In our project involving a quadruped robot, we have undertaken the creation of a leg replica designed specifically to serve as a test bench. This strategic decision stems from a comprehensive rationale rooted in the need for thorough optimization and experimentation. By having a replicated leg dedicated to testing, we gain the flexibility to implement and assess a range of optimization changes. This includes fine-tuning parameters, adjusting control algorithms, and exploring different configurations to enhance overall performance. Additionally, the leg test bench allows us to conduct various tests, scrutinizing factors such as stability, efficiency, and response to different terrains or scenarios. This approach provides us with a controlled environment where we can iterate and experiment with different strategies before implementing changes on the actual quadruped robot. Ultimately, the leg replica serves as a valuable tool in our project, facilitating a systematic and iterative optimization process to ensure the robustness and efficiency of the final quadruped robot design.

Building on the rationale outlined for the creation of the leg replica, our key objectives for this test bench, referred to as the fifth leg, are intricately tied to the principles of "Portability," "Swapability," and "Modularization." The objective of portability is to ensure that the fifth leg, our leg replica, is easily transportable and adaptable to various testing environments. This allows us to assess the performance of the quadruped robot in diverse conditions, contributing to a comprehensive understanding of its capabilities and limitations. Portability enhances the versatility of the test bench, making it feasible to conduct experiments in real-world scenarios. Furthermore, portability allows us to transport the leg to outreach events, allowing us to showcase the test bench and emphasize the need for testing in engineering-related scenarios. Next, swapability is a key objective aimed at facilitating the rapid interchangeability of components within the fifth leg. This feature enables us to experiment with different configurations, materials, or control algorithms seamlessly. By promoting quick and efficient swaps, we can systematically assess the impact of various changes on the leg's performance, contributing to the overall optimization process of the quadruped robot. Finally, modularization emphasizes the design of the fifth leg's components in a modular fashion. Each module is designed to be independent yet easily integrated, allowing isolated testing of specific elements. This modular approach streamlines the identification of optimal configurations, enabling us to focus on refining individual components or subsystems. The modularization objective promotes a systematic and targeted approach to experimentation and optimization.

Guided by these objectives, the team established a set of technical expectations for the fifth leg, emphasizing functionality, versatility, and adaptability. The primary design requirement mandated that the fifth leg stand must proficiently execute and record both kinematic and load testing, offering a dynamic platform for refining and optimizing the robot's movements.

Furthermore, the need for code flexibility during testing was underscored, requiring the stand to facilitate code changes before its application to the robot. The second design requirement focused on enhancing visibility and testing capabilities, demanding that the fifth leg stand design ensure a clear and unobstructed view of the leg. Additionally, it necessitated the incorporation of a method to apply at least one adjustable load on the leg, providing a controlled environment to assess the leg's performance under varied conditions. The third design requirement aimed for comprehensive testing scenarios, mandating that the fifth leg should demonstrate the capability to perform a walk cycle at variable speeds with diverse loads applied. This requirement reflects the team's commitment to replicating real-world conditions and optimizing the leg's functionality across a spectrum of dynamic situations. With these concise design requirements in mind, the team embarked on the task of replicating the legs of the robot, ensuring that the fifth leg not only meets but exceeds the set expectations, serving as a robust and versatile test bench for the iterative optimization of the quadruped robot.

5.2 Hardware and Physical Components Overview

Considering the RamBOT is both a multi-year project and also has many moving components and parts to enable functionality, a serious concern that developed was the strength and durability of the 3D printed parts. Previous year's teams printed parts using mostly PLA and PETG, using large infill percentages; to decrease project costs and weight, while maintaining strength, time was spent optimizing the shape and amount of infill within these parts. Multiple experiments were run to test how different loading conditions and strength requirements matched up with each material. A multitude of studies already exist on what materials work best for each application so this was utilized to quantify our findings. This includes basic tensile strength tests in CSU's Materials Lab to validate what we were finding from the results online.

However, this optimization did not take into account durability. As parts became worn down from loading and mechanical motion, the decision was made to look into different materials to increase durability, such as Nylon and HIPS. Concurrently, FEA was performed on the parts with the most noticeable wear and fatigue so that the team would have a better grasp on the stresses and loading that these parts were subjected to.

The material investigation primarily took place within CES, where data was gathered on the four different materials of interest: PLA, PETG, Nylon, and HIPS. The properties looked at included tensile strength, yield strength, and specific strength.

Additional work was put into the modification of 3D printing settings. By altering the infill percentage, the parts themselves could be made more resilient to applied tensile forces. Another modification made was changing from the default infill shape to the recommended cubic shape instead of the gyroid (Figures 7 and 8).

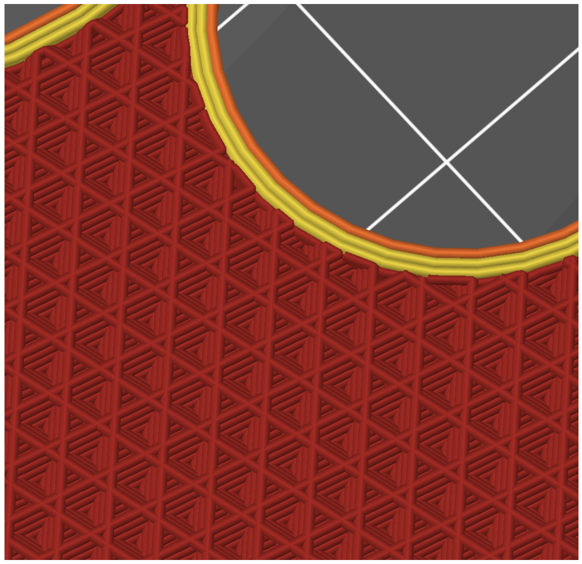

Figure 7: 3D Print Cubic Layer Style

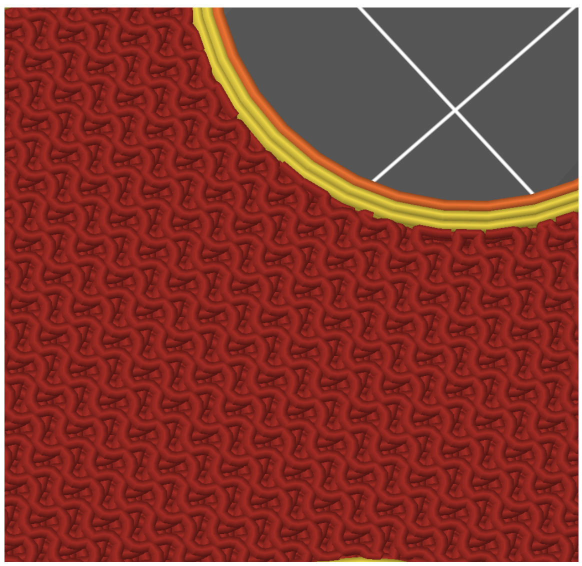

Figure 8: 3D Print Gyroid Layer Style

Table 1: Material Properties

Material	Yield Strength (ksi)	Tensile Strength (ksi)	Specific Strength (lbf-ft/lbm)
PLA	7.98-10.4	6.82-10.2	1.47e4-1.92e4
PETG	6.95-7.67	8.7-9.57	1.26e4-1.4e4
Nylon	87-152	87-152	1.76e5-3.05e5
HIPS	2.76-6	2.9-6.19	6.09e3-1.32e4

As can be seen from the table, Nylon is significantly stronger than any of the other materials, with a higher stress limit before permanent deformation, stress limit before fracturing, and resistance to permanent deformation per mass. These are all qualities to be looked for in materials to be used for high-load components; as an example, the gears within the RamBOT's cycloidal drives experience significant torque and loading due to the 10:1 speed reduction design.

Using all this experimental data and optimizations, the team created the fifth-leg testbench shown in Figure 9 by fabricating a fifth RamBOT leg, attaching it to a stand made from a combination of 3D-printed components and aluminum bars, and then connecting it to a system set-up similar to the complete RamBOT, but modified to be more accessible for rapid testing changes and only a fourth of the motors.

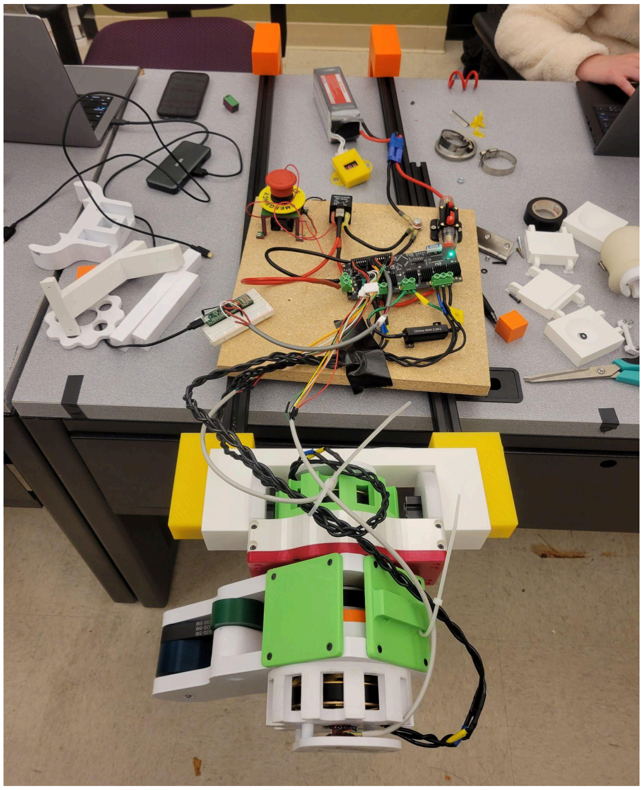

Figure 9: Test Stand in Partial Assembly

5.3 Communication Connections

The goal of the single leg project is to replicate the robot's legs in a simplified environment. In this context, the wiring and communication protocols of the leg resemble closely those implemented on the actual robot. There are a few major simplifications that can be leveraged to perform tests using the testbench. These simplifications are not in vain as they ensure a controlled environment to perform tests.

The control for the single leg revolves around the Teensy microcontroller. The Teensy runs the exact same code that is or will be deployed on the robot. This ensures the portability of software from the testbench to the robot. To reprogram the Teensy it must be reflashed using the Arduino IDE on a Linux, Windows, or Mac device. Managing the source of this code is vital for removing variables while testing. Git is used extensively to verify the version of the flashed code flashed to the Teesny. The Teensy itself does not create commands to be sent to the single leg. Instead, it acts as a translator between higher-level commands and the ODESC motor drivers. Therefore the Teensy receives higher-level commands from the USB serial bus and translates those commands into control signals sent to the ODESCs through pin serial buses. Additionally, the Teensy is powered through the USB cable connected to a Raspberry Pi or another computer.

The high-level commands are sent from either a Raspberry Pi or a computer. These high-level commands represent the instructions that the single leg should carry out. For example, this could be a run walk motion for ten seconds, or perform three push-ups. These commands can be interpreted from a PS4 controller or preprogrammed for automated testing purposes. The Raspberry Pi or computer is powered by a wall outlet or a self-contained battery for laptops.

As opposed to the six ODESC motor drivers found on the robot, the testbench only has one because the single-leg uses only two motors. The ODESC performs translation between the Teesnsy signal to power signals that drive the motors. This acts as another level of abstraction which ensures an easy debugging procedure. More details on the ODESC's functions are provided in Chapter 4. The ODESC on the single leg is powered by the same model 22.2V LiPo battery found on the robot. The ODESCs receive the Teensy control signals from a serial bus.

The single leg testbench only features two motor and encoder pairs. Again this is another aspect where the robot has been simplified from twelve to two motors. These two motors actuate the leg on the test bench. The motor is paired with an encoder to form a closed feedback loop utilized by the ODESC to create precise movements. When the encoder does not send proper feedback the loop is considered open and the leg goes limp. The motors and encoders are powered and controlled by the ODESC.

Communications and connections are greatly simplified on the single leg testbench. Thus the testbench can fulfill its purpose as a debugging tool for the robot. When there is an issue with either the communication or connection with a specific leg on the robot it is difficult to identify the exact location in the abstraction hierarchy where the problem is present. With simplifications to that hierarchy, the leg can easily be debugged by executing various automated tests.

Chapter 6. Standards and Tools

In developing our quadrupedal robot project, we embrace its open-ended nature while adhering to essential standards that define it as both an open-source initiative and an educational tool. Central to our approach are the principles of documentation, reproducibility, and safety. Ensuring the safety of our project, especially given its educational focus and potential interaction with children, remains our paramount concern. Rigorous safety measures have been implemented at both hardware and software levels to create a secure environment.

To fortify our safety protocols, our team has diligently worked to adhere to the Occupational Safety and Health Administration (OSHA) standards, specifically focusing on electrical wiring and battery safety. The OSHA standard on "Electrical Wiring Methods" (29 CFR 1910.305) is a comprehensive set of regulations crafted to guarantee the safe installation and utilization of electrical wiring and equipment in workplaces. Recognized under OSHA's General Industry regulations, compliance with this standard is imperative for maintaining a secure working environment. Early in our project, we identified sections of wire with compromised casings, exposing conductive materials. Section 29 CFR 1910.305 subsection F emphasizes that "all conductors used for general wiring shall be insulated" [4]. In strict adherence to this industry standard, we promptly replaced the wiring to mitigate the risk of electric shock. Furthermore, our commitment to OSHA standards extends to breakers and emergency stops. According to 29 CFR 1910.305 subsection C guidelines, "circuit breakers used as switches shall be connected so that the terminals supplying the load are de-energized when the switch is in the open position" [4]. Thus, strategically placed emergency stops, breakers, and relays serve as integral components designed to prevent injuries to team members and observers. In particular, we ensured that all breakers used on the RamBOT were up to code and we incorporated additional breakers into the design of the new fifth leg to guarantee full compliance with these safety measures. Furthermore, we selected components and wires with user safety at the forefront of our minds. We took care to avoid exceeding power limits, and within the software, we established strict current and torque limits. These measures serve to safeguard both the hardware components and individuals nearby, reinforcing our unwavering commitment to creating a secure and reliable project environment.

In addition to electrical hardware standards, our team worked to comply with 3D-printed hardware standards. As highlighted throughout this paper, it became evident early on in the project that certain 3D-printed parts exhibited wear over the course of the two-year project. In response, our team conducted exhaustive testing and validation of both new and improved 3D-printed designs. Employing CES for materials analysis, we adhered to American Society for Testing and Materials (ASTM) standards to determine compressive strength and modulus of 3D printed parts. In particular, our project adheres to ASTM D695, a test method used to determine the compressive properties of un-reinforced and reinforced plastics [5]. ASTM D695 obtains the properties of a material's compressive strength, compressive yield point, and modulus. For our project, this helped us determine the compressive strength and modulus of 3D printed parts with different infill densities and materials. Furthermore, for a detailed understanding of stress and load distribution in our designs, we utilized Abaqus, a Finite Element Analysis (FEA) software. Abaqus allowed us to establish loads and conditions, pinpointing areas of stress and strain. This informed our strategy for reinforcing those specific areas to improve overall structural integrity. Solidworks, a robust Computer-Aided Design (CAD) software, played a pivotal role in our iterative design process. It facilitated rapid prototyping of both existing and novel components, such as the leg stand, enabling us to refine and innovate with efficiency. To translate our CAD models into tangible 3D printed parts, we employed Prusa Slicer, converting CAD files into G-Code for the Prusa 3D printers. This streamlined the printing process, allowing for precise and reliable fabrication. In the final stages of refinement, hand tools like the dremel, electric drill, screwdriver, and wrench were instrumental in fine-tuning the shapes of parts and ensuring a precise fit. The bandsaw, hacksaw, and vices played a crucial role in crafting the platform on which the fifth leg rests and securing it firmly to the table.

Along with adhering to industry standards for hardware deployment, we also diligently worked to align with software protocols through widely recognized industry tools. The utilization of Google Docs emerged as a cornerstone in crafting comprehensive how-to guides. By centralizing these documents in a shared Google Drive, accessibility and information sharing among team members became seamless, fostering a collaborative environment. For schematic designs, we turned to the industry-level software Circuit Diagram, ensuring precision in creating and labeling schematics. This approach allowed us to employ conventional symbols and material names that can be universally understood in the industry, extending the usability of our documentation beyond our team. In the realm of code deployment for the Teensy and Raspberry Pi, Visual Studio Code (VSCode) proved instrumental. The platform facilitated cloning repositories, creating branches, making modifications, and updating the main branch. This not only empowered us to make significant updates but also encouraged adherence to best coding practices by managing changes in dedicated branches before merging into the main codebase. Similarly, the leg initialization code received updates through the Arduino IDE, enabling real-time interfacing with the Teensy and ODESC mechanics. All updated code, developed through the Arduino IDE and VSCode, was incorporated into our team’s GitHub, facilitating comprehensive documentation and allowing public access to our work. Furthermore, the code and accompanying documentation prioritize clarity, utilizing comprehensive naming conventions and comments for clarity and readability. The changes made to the leg initialization code to make it more user-friendly and efficient exemplify this aim of pinpointing errors swiftly and providing a seamless experience for those replicating the project. Finally, adjustments to the ODESCs were facilitated by the ODrive tool, streamlining the process of connecting to each ODESC and updating parameters efficiently.

To effectively monitor our team's progress, our team integrated several industry-standard management tools. Throughout the semester, individual weekly activities were consistently logged in an Excel spreadsheet. However, recognizing the limitations of this method in capturing group challenges, we implemented Jira as the semester progressed. Jira allowed us to create tickets for issues, enabling a more organized and accessible approach to problem-solving. Team members could easily identify tasks that needed attention and claim them based on available time and expertise, enhancing task visibility and collaboration. For effective communication and information retention, our team relied on Discord. This platform served as a central hub for messaging, storing critical images, documentation, and event information, facilitating efficient and organized team discussions.

Chapter 7. Conclusion

As the RamBOT continues to move through its third year as an Electrical Engineering project, a strong focus on reliability and improvement has been a priority. The previous two years consisted of constructing a working first prototype of the RamBOT, but the focus of the first semester of the third year was focused on various improvements to make the robot overall a better machine. Our various improvements to the initialization process allowed the system to be initialized and operated much more easily, allowing us to improve the robot in a myriad of other areas. The construction of the testing stand allowed for improvements to be made in both hardware and software. The addition of the LiDAR system will improve the safety of the robot for future outreach events and overall documentation rehauls will make continuation of this legacy project far simpler in the future. Currently, the RamBOT team is attempting to increase the performance of the robot and resolve physical stability issues while the robot is in operation. These upgrades will be accomplished with both code updates and optimizations of the hardware as shown in Appendix C. Ultimately, the changes and improvements implemented this semester will help promote reliability and safety as the team progresses into future semesters.

Chapter 8. Future Work

Moving forward, the testing stand will continue to be utilized to make improvements to the RamBOT device. Currently, the submodule is able to take inputs from a computer or program. From there it is capable of acting exactly how one of the legs on the RamBOT would behave. Moving forward, developments will continue to be made in the realm of testing and optimization. The force-loading stand is almost complete, but a little more work will need to be done to test its validity. Once this is verified to be operating correctly, we will move towards the utilization of this device for optimization and testing procedures. In terms of optimization, the test stand will be beneficial in testing new parts that are in the works, such as gears and transmission belt shafts. Currently, PLA is used for a majority of parts but to test out the new parts that are being implemented, the testing stand will be useful for testing these parts before full implementation on the RamBOT. Additionally, this stand will be utilized to run tests on the leg, specifically loading a force onto the leg using a weight system and having the leg go through a walk cycle at different speeds. This will allow for the understanding of the maximum load the leg can withstand as well as give information on how to allow the leg to operate slower during usage, something that was desired by the team early on.

Another prospect that will be beneficial in the coming semester is to improve the quantity of modeling that the RamBOT system has. The team plans on implementing future FEA models of the parts to understand the performance of the device. This will also go hand in hand with other hardware modeling that needs to be performed for the kinematics. A goal that the team has is to improve the understanding of how tuning directly impacts performance. This will ultimately make it easier to apply changes to the code and understand what that would do to the device without having to turn the RamBOT on. This can be done using the MATLAB Simulink toolkit and will provide a variety of interesting insights.

Improvements to the RamBOT also will come in terms of hardware improvements. Much was done this semester to improve the lifespan of the machine by changing parts out. However, there is still a need to change more parts so the robot can operate at its full potential. This will come in the form of implementing some new material changes and changing the device assembly by adding new parts or improving the current device machine assembly (adjusting bearings, part interactions, and more).

One of the larger issues still faced by the robot is the unreliability of all wire connections. There has been no strain relief implemented in the RamBOT at all, and as a result, wires have come unplugged and solder joints have come apart while the team is fixing other issues on the robot. This has set the team back many times because it is not always immediately obvious that something is unplugged which can set back troubleshooting by a lot. Therefore, a focus for next semester will be to implement strain relief on the robot to prevent future issues of this kind.

There are a few key areas on the robot where strain relief will be implemented. The first is at the motor and encoder wire connection points on the legs. The encoder wire connections are soldered on, and as the robot walks it pulls on the wires and connections. This is unsustainable and will be remedied. The second area of concern is inside the robot. There are many wire connections that are joined together with plugs. These plugs have been known to come unplugged when the team is opening the ODESC panels to work on various issues inside the robot. Since there are so many wires in that area, it is not immediately visually obvious when a wire is unplugged. Therefore, it is important to design something to lock the plugs together so they will not disconnect and cause issues in the RamBOT. The last area of concern is the connections to the ODESCs themselves. There are both soldered wires and plugged wires connected to the ODESCs. The solder joints have a chance of breaking as the robot is being worked on. The plugged wires pull on the ODESC ports, which over time will break the ODESC ports and therefore the ODESCs themselves. Both of these issues will need to be remedied to prevent future issues with the ODESCs.

In our strategic roadmap for the integration of machine learning (ML) models into our robotic systems, the initial crucial decision centers around choosing between repurposing an existing team's model or crafting a new one tailored to our specific requirements. This decision forms the foundation for subsequent actions, as the selected model, whether recycled or newly designed, undergoes meticulous training with a specialized focus on the classification of a ball—an elemental feature crucial for the seamless navigation and interaction of our robotic systems in dynamic environments.

Following this, our strategy advances into the development of a sophisticated algorithm dedicated to ball detection. Advanced computer vision techniques are employed not only for identifying the ball but also for guiding the robot effectively towards its location. A key innovation in this process is the strategic integration of Lidar technology, serving as a sophisticated distance-measuring tool. This ensures that the robot maintains precise spatial awareness, contributing not only to the model's robustness but also enhancing the overall adaptability of our robotic systems to diverse environments.

Moving beyond mere detection, our strategy encompasses the intricacies of predicting the ball's trajectory. This involves formulating a methodology to decipher the direction and velocity of the ball, tapping into the capabilities of monocular vision to anticipate the trajectory and facilitate a proactive response from the robot. By integrating these elements—model selection, targeted training, advanced algorithm development, Lidar integration, and trajectory anticipation—our comprehensive strategy aims to position our robotic systems at the forefront of technological innovation. We hope to make this subsystem robust enough so that we can ensure that our goal of playing fetch with Sparky can be met by E-Days.

References

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[4] “Wiring methods, components, and equipment for general use.” https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.305 (accessed December 09, 2023)

[5] “ ASTM D695 Compression Testing Rigid Plastics.” https://www.instron.com/en/testing-solutions/astm-standards/astm-d695-plastics (accessed December 09, 2023)

[6] “AS5047P Product Document” https://ams.com/documents/20143/36005/AS5047P_DS000324_3-00.pdf (accessed December 08, 2023)

Appendix A - Abbreviations

- ASTM - American Society for Testing and Materials
- CES - Cambridge Engineering Selector
- CSU - Colorado State University
- ECE - Electrical and Computer Engineering
- EDays - Engineering Days
- EIR - Engineer In Residence
- FEA - Finite Element Analysis
- HIPS - High Impact Polystyrene
- IDE - Integrated Development Environment
- LiDAR - Light Detection and Ranging
- LiPo - Lithium Polymer
- OSHA - Occupational Safety and Health Administration
- PETG - Polyethylene Terephthalate glycol
- PLA - Polylactic Acid
- STEM - Science, Technology, Engineering and Mathematics
- VIP - Vertically Integrated Person
- VSCode - Visual Studio Code
- 2D - Two-Dimensional
- 3D - Three-Dimensional

Appendix B - Budget

The total budget for this year's team is $2,196.00 with an additional $225 for purely outreach specific purchases. The team initially received $200 for each senior on the project for a total of $1,800, and then we received an additional $396 that was leftover from the previous year's team. The team planned on using this money to buy hardware, electronics, and other miscellaneous items as detailed in Figure 10 down below. The team at the conclusion of the first semester has spent a total of $1,193.06 from our ECE Sr. Des Fund, and the details of the items purchased are shown in Figure 11 down below. The team plans on purchasing more items for the second semester to ensure there are extra parts in case of item failures, increase the reliability of the project by replacing parts, and to continue to complete the team's goals. All of the items purchased thus far have been integral to building the fifth leg test bench detailed in Chapter 5, replacing parts on the robot, and ensuring the team has extra parts in case components fail.

The team utilized Colorado State University's engineering 3D printing labs extensively totaling to around 160 printing hours. The only cost for the team was purchasing 3D printing filament that was purchased. The total manual hours that the team members have put into the project for this semester rounds to around 990 hours.

Subgroup	Item Name	Price	Quantity	Total	Notes
Hardware					
	Screws, washer, bolts, nuts	$75.00	>1	$75.00	Reference OpenDog V3 Bill of Materials in Inventory
	Bearings	$300.00	>1	$300.00	Reference OpenDog V3 Bill of Materials in Inventory
	Carbon fiber rod for spare leg	$30.00	1	$30.00	
	Belts	$15.00	2	$30.00	1 for spare leg, one for spare
	Other:	$30.00	1	$30.00	
Electronics					
	PI-4	$90.00	1	$90.00	
	O-DESCS	$250.00	2	$500.00	
	Arduino Teensy	$40.00	1	$40.00	
	Battery	$45.00	2	$90.00	Need to test extra batteries
	Motor Encoder	$20.00	2	$40.00	
	LIDAR Sensor	$150.00	2	$300.00	
	5V Voltage Regulator	$5.00	1	$5.00	
	Microphone	$25.00	1	$25.00	
	Google Colab Subscription	$70.00	7 months	$70.00	
	Other:	$30.00	1	$30.00	
Other					
	3D Printing Filament	$23.00	3	$75.00	
	Label Maker	$40.00	1	$40.00	
	T-Shirts	$15.00	2	$30.00	
TOTAL				$1,800.00	

Figure 10: Planned Budget for Semester 1 and Semester 2

			Out of which fund				
Date of purchase	Amount	Explain what component; include link and explanation, if needed	Professor	ECE Sr.Des. Fund	Personal	Other#1	Other#2
9/22/2023	$226.13	1. Raspberry Pi 4: https://a.co/d/cxLnruK 2. LIDAR Sensor: https://a.co/d/4ei40MK 3. White 2 Pack 1.75 mm Filament: https://a.co/d/86M6JVz		Asked Hein to purchase for the team			
10/1/2023	$185.74	1. Belt (HTD 5M pitch 630 length): https://a.co/d/1By6AqH 2. Carbon Fiber Rod (28mm OD, 1mm+ wall thickness) 2 count: https://a.co/d/eYxFT9A 3. Internal Cycloidal Drive bearings: https://a.co/d/4CqA4jq 4. Cam and cap Drive bearings: https://a.co/d/dArqVS4 5. Knee idler bearings: https://a.co/d/8Rt1uzZ 6. Drive Case Screws: https://a.co/d/bGNAefc 7. Emergency Stop Switch: https://a.co/d/7QxzXRb 8. Electronics Power Switch: https://a.co/d/5JdLohB 9. Cycloidal Drive cam (M3 15mm thread length): https://a.co/d/7QQpVUQ 10: Cycloidal Drive output (M4 hex heads 80 mm): https://a.co/d/d1b4M1p 11. TEENSY: https://a.co/d/2eXY4og		Asked Hein to purchase for the team			
10/10/2023	$194.56	1. 4mm x 100mm length Rods: https://a.co/d/2WDL6bH 2. 604ZZ Ball Bearings: https://a.co/d/f51AapJ 3. 6706ZZ Bearings: https://a.co/d/cWqq1m5 4. M4 Washers: https://a.co/d/fFCUy51 5.Nylon Nuts: https://a.co/d/fFCUy51 6. Nylon Spacers: https://a.co/d/6vIW2IW 7. Google Coral USB: https://a.co/d/0n4xWcx 8. Hex Drive Flat Head Screws: https://www.mcmaster.com/products/hex-head-screws/system-of-measurement~metric/thread-size~m3/length~18-mm/fastener-head-type~flat/drive-style~hex/finish~black-oxide/ 9. M4 Hex Head Screws: https://www.mcmaster.com/products/din-933-cap-screws/thread-size~m4/length~70-mm/fastener-head-type~hex/		Asked Jackie to purchase and Hein Placed Order			
10/16/2023	$158.49	1. ODESC3.6: https://a.co/d/6TzYhyR		Asked Jackie to Place Order			
10/18/2023	$89.89	1. Touch Screen Monitor: https://a.co/d/iQD2lca 2. Camera: https://a.co/d/epPqDNq		Asked Jackie to Place Order			
10/23/2023	$31.89	1. Carbon Fiber Rod: https://a.co/d/9CISv7t		Asked Jackie to Place Order			
11/8/2023	$260.78	1. Lithium Polymer Battery: https://a.co/d/ih6GsGj 2. White PETG: https://a.co/d/2Bg83AI 3. Anti-Slip Pads: https://a.co/d/13ADgPq 4. Metal C-Clamps: https://a.co/d/36kQ2pE 5. High Precision Power Analyzer: https://a.co/d/gqhGRCG 6. Gorilla Epoxy: https://a.co/d/8BmPyL0 7. Super Glue: https://a.co/d/3O8awiG 8. Metric Allen Key: https://a.co/d/c4ytdPY 9. USB Speaker: https://a.co/d/fscUbqq 10. Hex Drive Flat Head Screws: https://www.mcmaster.com/products/hex-head-screws/system-of-measurement~metric/thread-size~m3/length~18-mm/fastener-head-type~flat/drive-style~hex/finish~black-oxide/ 11. Electric Screwdriver: https://a.co/d/hP9DsoW 12. Nylon Filament: https://a.co/d/8DEfDey		Asked Jacki to Place Order			
11/8/2023	$45.48	Two 128 GB SD Cards		Hein purhased in person			

Figure 11: Summary of Items Purchased for Semester 1

Appendix C - Project Plan Evolution

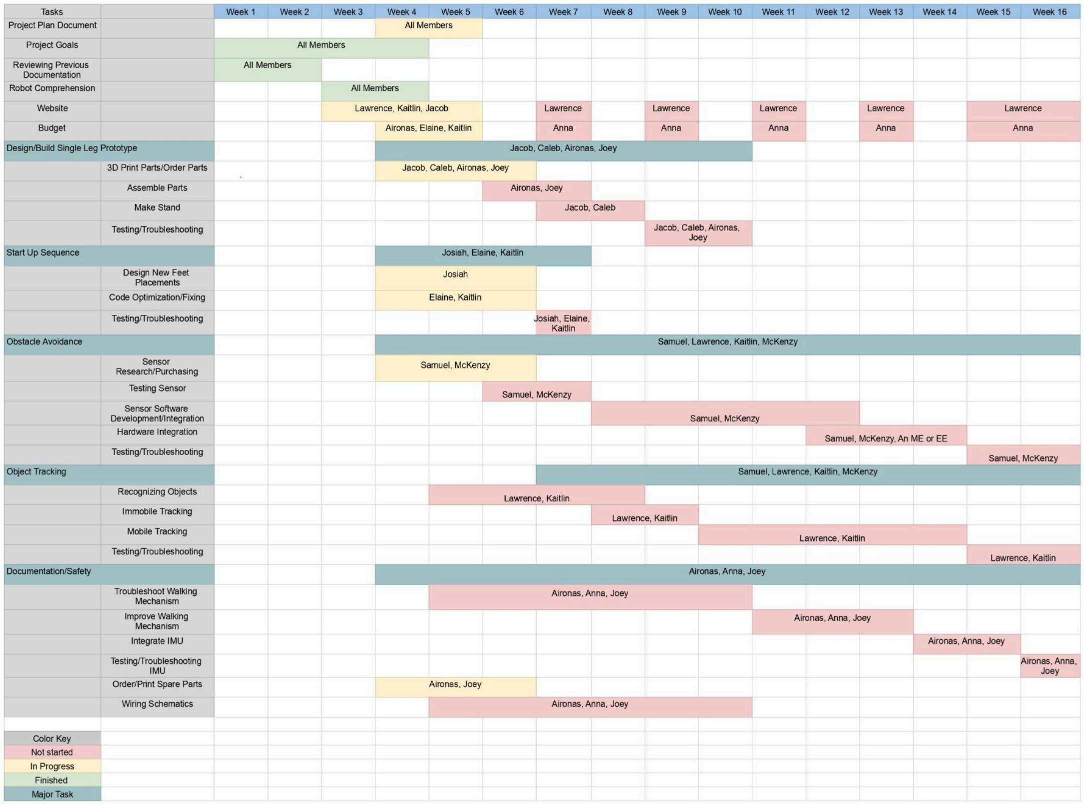

Figure 12: RamBOTs Timeline, Version 1 Semester 1.

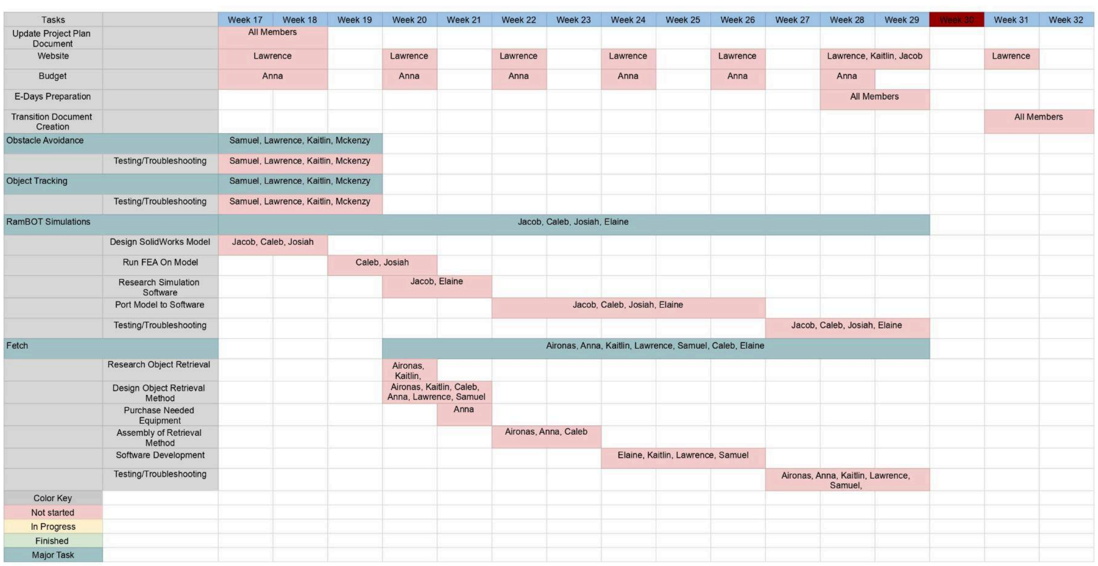

Figure 13: RamBOTs Timeline, Version 1 Semester 2.

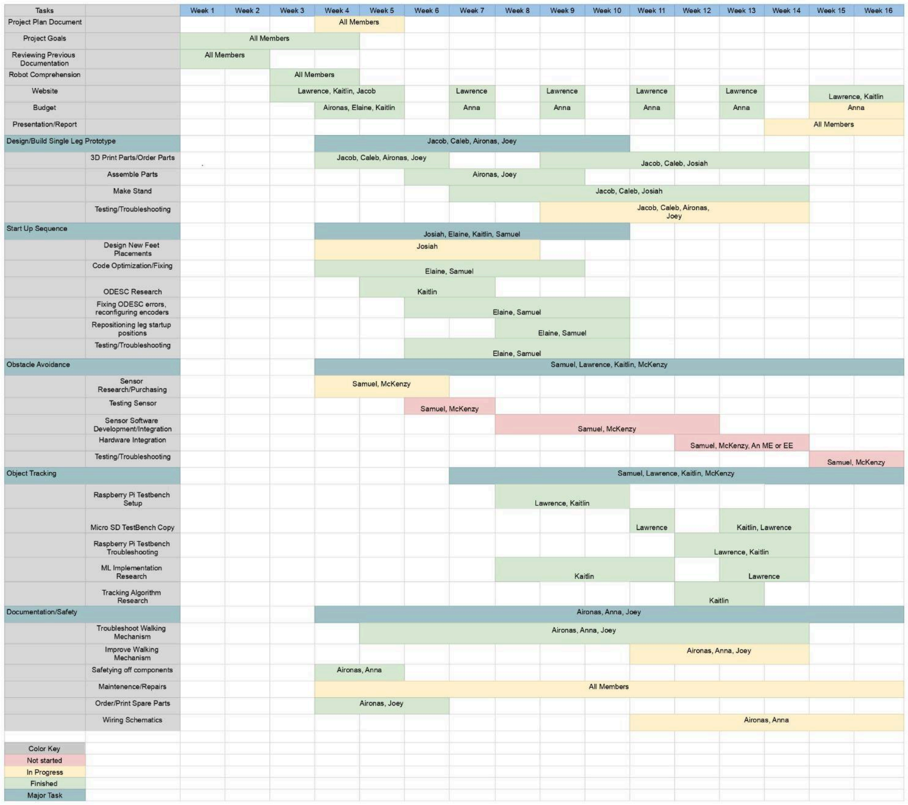

Figure 14: RamBOTs Timeline, Version 2 Semester 1.

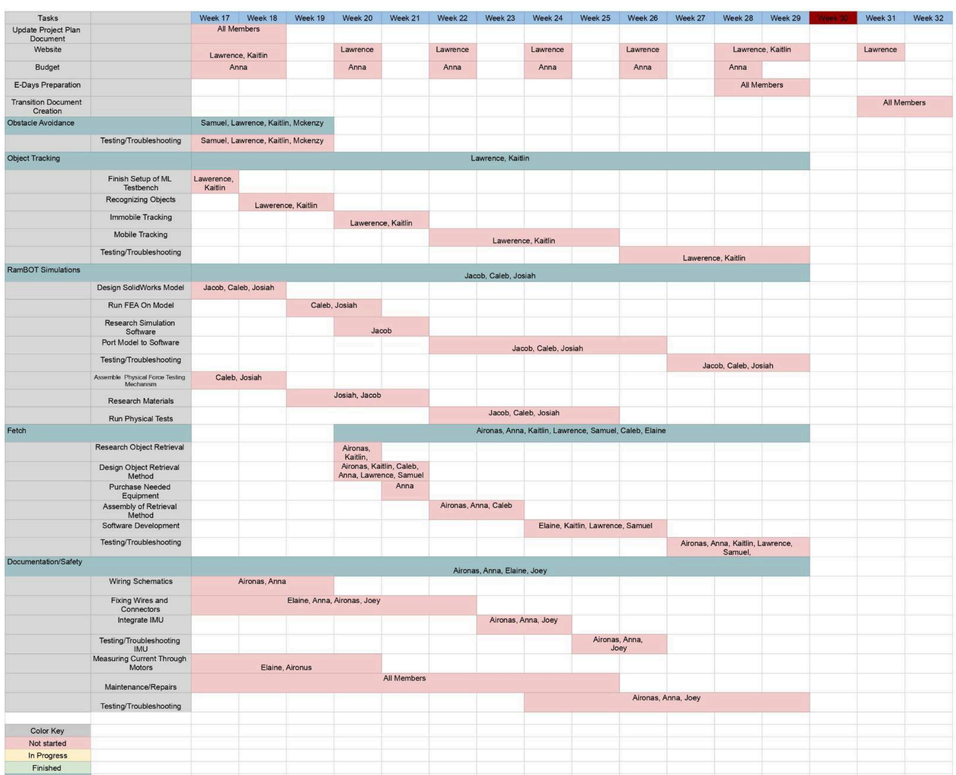

Figure 15: RamBOTs Timeline, Version 2 Semester 2.

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