4-26-2023

Autonomous Planetary Rover Final Project Report

Nolan Anthony
Trinity University

Gabriella Gonzalez
Trinity University

Clyde Johnson
Trinity University

Aislinn Marcee
Trinity University

Final Project Report

Autonomous Planetary Rover

Nolan Anthony, Gabriella Gonzalez, Clyde Johnson, Aislinn Marcee

Dr. Keith Bartels, Team Adviser

April 26th, 2023

Executive Summary

This report documents the 2022-2023 Autonomous Planetary Rover Team's work. The main focus and goal of our team was to improve the locomotion of the rover through mechanical improvements to the suspension and steering systems. The final expectation for the rover given by our sponsor, Dr. Kevin Nickels, was for the rover to complete an obstacle course where it drives over obstacles the height of the radius of its wheel, traverses uneven terrain, and completes turns with a 12-inch turn radius. The main inspirations for our design of the suspension and steering systems come from previous planetary rovers that have completed missions on Mars and the Moon, specifically Curiosity and Sojourner. We have done substantial research on the mechanics of the rocker-bogie suspension system and have chosen this as our method of robust suspension. We also researched different methods of steering and settled on an independent steering system. In terms of primary subsystems, we have focused on suspension and steering, though we will also discuss design choices related to the chassis material and electronic components.

This project has been evolving and changing for multiple iterations—four previous teams have worked on the rover, each team focusing on different aspects of improvement. Our team is focusing on improving the mechanical aspects of the rover while making use of previous teams' additions to the project, but will not focus on any systems related to the autonomous navigation of the rover. This year, the design problem was to mechanically improve the rover so that it was capable of going around and over obstacles in a simple obstacle course. Requirements of the design also included the Rover's ability to carry a 100-pound load (to simulate experimental equipment) and to traverse over obstacles as tall as 5.1 inches (the radius of the wheels). These design requirements fed into project-specific requirements from our sponsor, which included having a rocker-bogie suspension system and independent steering. Another requirement was the capability of the rover to pass through a standard door frame in Trinity University's CSI Building. These requirements reflect constraints of real planetary rover design, and will force us to consider environmental factors on the design. In this document, we will discuss all conducted tests and to what extent these tests showed that our prototype fulfilled each requirement.

Though individual design components of the rover proved to be successful, the overall prototype was unable to complete the required obstacle course due to issues with stability. The clearance, dimensions, and obstacle construction requirements were successful based on testing, and are important for the next steps of the rover. Some tests showed partial achievement of requirements, which demonstrate that the rover has been improved this year and is on the right track. The team concludes that the suspension system design is a partial success, as similar to the steering system design, because it functioned as expected though not integrated perfectly. The rover was able to be controlled by a joystick, and was capable of making wide turns - showing success for the desired independent steering design. The rover's ability to overcome obstacles was also deemed a partial success, as though it could statically handle being on top of an obstacle without tipping excessively, it was difficult for it to dynamically climb the obstacle. The team believes that each subsystem of the rover prototype shows promise, and look forward to seeing future iterations.

I. Introduction

As provided by the project sponsor, Dr. Kevin Nickels, the Autonomous Planetary Rover will be used as a mobile sensing platform that will test autonomous navigation software in extreme environments, while also collecting geologic data in the field. To successfully produce this mobile sensing platform, previous design teams have designed and constructed the chassis and driving mechanisms for the rover. In the design overview, improvements to the mechanical aspects of the rover will be discussed at length, but no improvements were made on any systems related to autonomous navigation.

In addition to being able to traverse around or over obstacles in its path, the rover must also sustain high carrying loads and protect expensive equipment. Thus, our senior design team developed a rover prototype that has a suspension and active steering system that attempted to allow the rover to traverse over obstacles. More specific requirements include being able to traverse obstacles greater than or equal to the height of the radius of the rover's wheels, maintaining a body clearance of ten inches, navigating around or over obstructions without tipping over, completing turns with a 12-inch turning radius, and protect a load of 100 lbs. In order to meet the aforementioned objectives, requirements, and working criteria, the team implemented a rocker bogie suspension with six driving wheels and four independent steering wheels.

II. Overview of the Final Design

Our design work this year was primarily focused on mechanical aspects of the rover that needed improvement. We broke down our design into one minor and three major subsystems: body, suspension, steering, and electronics. The main design components that were kept from the previous team were the frame, the gearboxes, and the overall materials choice of 80/20. Our primary focuses were the suspension and steering systems, as finalizing them will set the next teams up for success. To have a final prototype capable of fulfilling our design requirements, we took inspiration from previous design teams on this project as well as planetary rovers launched by NASA. Previous design team prototypes also included a rocker-bogie suspension system seen in our final design, which was improved upon to better incorporate the steering system. The steering system we decided to implement is an active steering system, with four steering motors and six driving motors. The six drive motors are brushless DC motors which have built-in speed controllers and operate at 12V. The four independent stepper motors also operate at 12V, and are controlled using external bipolar stepper control boards. These boards and the internal speed controllers of the BLDC motors are controlled by an ESP32 microcontroller development board. In terms of resources, the team was able to take full advantage of the Makerspace and Electronic shop available to us at Trinity. Every subsystem includes pieces that were custom designed and fabricated by the team on site, such as milling, CNC, or 3D printing. A total fusion mockup of our final design can be seen in Fig. E1, and an image of the completed rover can be seen in Fig. 1.

Figure 1: Fully Constructed Rover

1. Subsystem Designs

Body/Chassis

The rover's chassis was designed and constructed by a previous senior design team. It consists of a frame made of 80/20 extruded aluminum, with a base made of wooden pegboard to allow for easy electronics mounting. The previous team used a base made of acrylic plastic, but because our project requirements include a 100 lb loading condition, our team changed the base to a wooden pegboard with 80/20 reinforcement members to increase the chassis strength and ability to interface with our electronics system. The project requirements applicable to this subsystem include its dimensions and its ability to support a 100 lb load. In terms of dimensions, one of our project requirements was for the rover to be able to fit through a standard CSI doorway measuring approximately 33.75 inches across. Because of this requirement, the rover chassis design could not be made any larger than the previous team had already made it, something which constrained our design choices for other subsystems. Another requirement which influenced the design of this subsystem was the 100 lb load requirement.

This subsystem was constructed by interfacing 80/20 extrusion members with each other using ¼ inch screws and t-slots. The wooden pegboard was installed using the same hardware. The members themselves were cut using the horizontal bandsaw in the Makerspace.

Suspension

The addition of a robust suspension system was one of two primary focuses for this project. Given the requirements for a robust suspension that can climb over obstacles as high as the radius of the wheel, as well as the required independence between the sides, the team chose to implement a rocker-bogie suspension design. The inspiration for this type of suspension was derived from research on previous Mars and Lunar rovers which have similar functions to the data-collecting planetary rover our team is constructing. The biggest inspiration for the team's vision is NASA's Sojourner, which was the first rover to implement the rocker-bogie suspension, and is the rover closest to our planetary rover in size and function.

A rocker-bogie consists of a larger "rocker" assembly and a smaller "bogie" assembly to maintain contact between the ground and all of its six wheels at any given time. It contains a hinged assembly (Fig. E1) that can adapt to different types of terrain by pivoting the position of the wheels, providing excellent stability to the chassis. The left and right sides of the suspension are connected through a differential bar (Fig. E2) so that each side of the rover can move independently and traverse different heights of terrain without tipping over or endangering equipment in the chassis. The project requirements that directly relate to the suspension include the implementation of a robust suspension, the ability of the rover to climb over five inch obstacles, the underbody clearance of ten inches, the ability of the rover to support a load of 100lbs, and the ability to traverse uneven terrain without falling over. Since the suspension is a fundamental component of the way the rover moves, all requirements except those specific to a steering system apply to this subsystem.

To best determine the relationship between the lengths of each of the leg members and the angles at which the members must meet to create a rocker-bogie suspension, we created a mathematical model (Fig. C1 and Fig. C2 in Appendix C) of the expected forces presented in our Preliminary Design Report. Using a force analysis, as well as trigonometry, we predicted the expected lengths, angles, and applied forces on each of the members (see Appendix C). Our design consisted of straight vertical columns to allow for the implementation of independent steering that introduced six total members to the suspension system instead of the typical four seen on the Mars rovers. The overall design of the suspension members and connections did not change from these predictions and calculations, but once we began implementation and construction of the rover we discovered that the overall height of the rover calculated in our model was too tall. While we maintained the main 127 degree joint connection (Fig. E3) for the rocker, and the overall dimensions of the bogie, we shortened all six legs to lower the rover's center of mass. Each member of the suspension was a length of 80/20 extrusion. The main joint used to connect the members of the rocker system was fabricated using the MarkForged 3D printer and was printed in composite nylon, seen in Fig. 2. The bogie joint consists of two oil-embedded sleeve bearings housed in each 80/20 member, connected using a ⅜"x3" partially threaded screw and nut to hold the joint together while allowing for a smooth rotation, seen in Fig. 3. The remaining joints connecting the leg members are aluminum cut using the HAAS Mini mill and designs from Fusion 360.

The suspension system also includes a custom fabricated differential bar that connects to the main joints on each side of the rover to allow for independent movement as well as provide restriction on the rover's range of motion. The differential bar is connected to the main nylon joints using two long double sided ball bearing joints that can pivot with the bar and the angle as they are moved. Since this joint is a fixed length, the differential bar can only rotate a certain distance before becoming constrained. This restrained range of motion prevents the rover chassis from rotating around the central supporting bar holding the two nylon joints. The bar itself was fabricated by cutting a Fusion 360 design out of an aluminum sheet using the ShopBot CNC machine in the Makerspace, seen in Fig. 4.

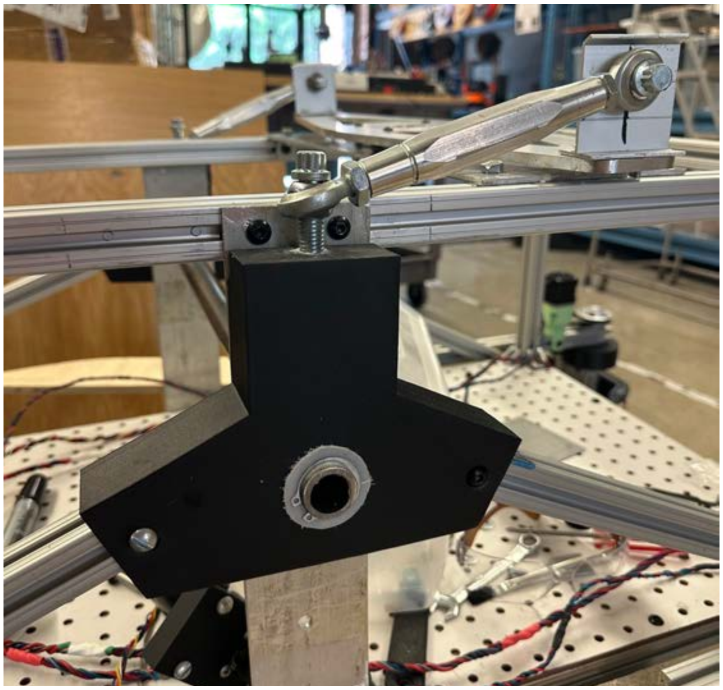

Figure 2: Rocker Joint Setup

Figure 3: Bogie Joint Setup

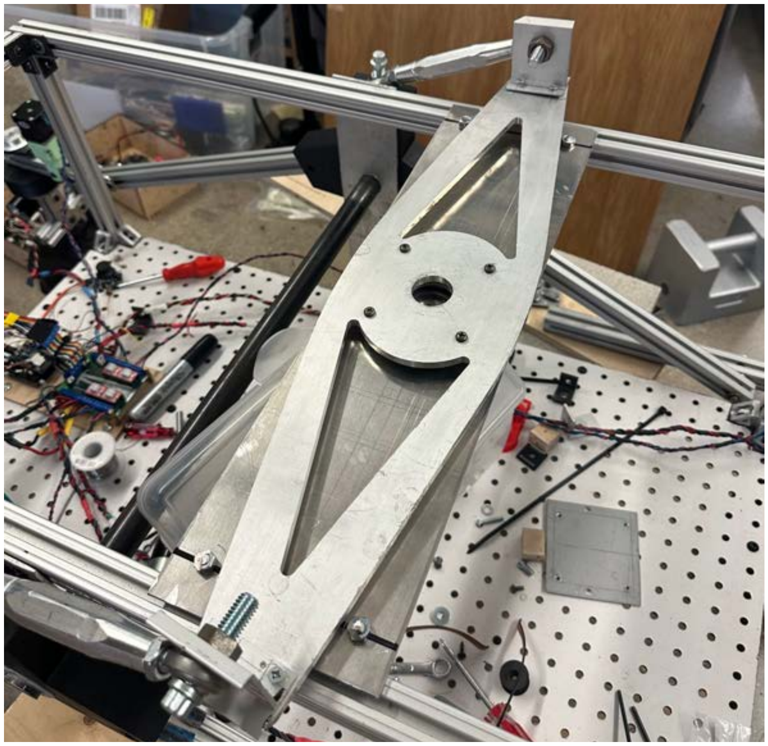

Figure 4: Differential Bar Setup

Steering

The final design for our steering subsystem was also influenced by our project requirements, specifically the requirement to implement an active steering system, the turning radius requirement, and the obstacle course requirement. Because one of our project requirements was to achieve a turning radius no larger than 12 inches, we decided to design and implement an independent steering system in the rover's outer four wheels so that we would be able to complete close to a zero degree turn. Additionally, because we needed the rover to navigate an obstacle course, it would be required to complete different types of turns. This requirement influenced our design as the rover's wheels needed to be able to turn independently to help increase maneuverability so that it could better traverse obstacles in the course.

To implement the required steering subsystem with the rocker-bogie suspension design, the team chose to introduce independent steering to the rover. The rover's independent steering system is used to steer each of the outer four wheels of the rover to allow for improved maneuverability. Each steering column (pictured in Fig.5) consists of a stepper motor, a belt pulley system, a nylon support, a vertical steering column, and a wheel and gearbox. Each stepper motor is mounted in a 3D printed motor mount (Fig. E4) on the outer four legs of the rover, and is connected to the vertical steering columns using a belt and pulley system. An 8mm steel shaft is housed inside the steering column, which passes through two flange bearings to allow for a smooth rotation. The 8mm shaft is then connected to the vertical steering column using a flange shaft mount, which is connected to a vertical piece of 80/20 using a custom machined aluminum mount (Fig. E5) from the HAAS MiniMill. The short 80/20 lengths that are used to construct the frame of the steering columns are held together using the custom machined aluminum brackets seen in Fig. E6 and mounted like in Fig. E7. When the stepper motors turn, the belt and pulley systems take advantage of a low gear ratio to produce enough torque to rotate the full steering column assemblies.

Construction of the steering system began by cutting the various lengths of 80/20 used in the steering column. After cutting all pieces to length, the custom steering column plates pictured in Fig. E5 were made on the HAAS mini mill in the Makerspace. These plates were used in conjunction with 80/20 T-nuts and screws to construct the frame of the steering column. Next an 8mm hole was drilled through the horizontal 80/20 member that the steering column shaft will be housed in. After this, the custom steering column base pictured in Fig. E5 was connected to the vertical steering column member using 80/20 mounting brackets and screws. After this step, an 8 mm shaft flange was attached to the steering column base using screws, and then the 8mm shaft was placed in the flange using its included set screws. Next, the custom 3D printed steering supports were press-fitted onto the steering column using a mallet. With the steering column assembly completed, two 8mm flange bearings were then attached to the horizontal 80/20 member on either side of the pre-drilled 8mm hole using 80/20 T-nuts and screws. The steering column assembly's 8mm shaft was then fed through the bearings, and the 8mm ID gear was then attached to the top of the 8mm shaft using its included set screws. Lastly, our custom 3D printed stepper motor mounts (Fig. E4) were then attached to the horizontal 80/20 member using 80/20 mounting hardware, and its belt was placed around the 8mm ID pulley and the stepper motor's pulley. These steps were then repeated to construct all four steering columns. To connect the steering columns to the main legs of the rover, the custom cut aluminum brackets seen in Fig. E8 were made using the HAAS mini mill and mounted using 80/20 t-slots and associated screws, as can be seen in Fig. 1. The final steering column design with the pulley and motor mount can be seen in Fig. E9. Lastly, the two middle wheels which did not have steering implemented were mounted to the bogie 80/20 member using the custom made 90-degree aluminum joint seen in Fig. E10.

The design for this subsystem has changed dramatically since its original conception presented in our Preliminary Design Report. Originally, our steering column was going to be made of a single vertical 80/20 length offset from the wheel; however, after some initial testing we found that this offset increased the moment of inertia of the steering column, causing us to change our design to one that was centered over the wheel so that it would require less torque from the steering motors. Testing validated this design change, however we found that our steering motors were still not strong enough to rotate the full steering column assembly. To address this issue, we then upgraded the steering column pulley to a significantly larger one to decrease our gear ratio so that we could achieve a greater torque. The final design change involved with the steering subsystem was the addition of the custom nylon supports printed using the MarkForged. Testing revealed that our 8mm steering column shaft was too thin, resulting in instability in the full rover assembly. This prompted us to design and 3D print the nylon supports pictured in Fig. E11. These supports increased the surface area of the contact point between the steering column and the suspension system, which helped to distribute some of the forces off of the thin 8mm shaft used in the steering column.

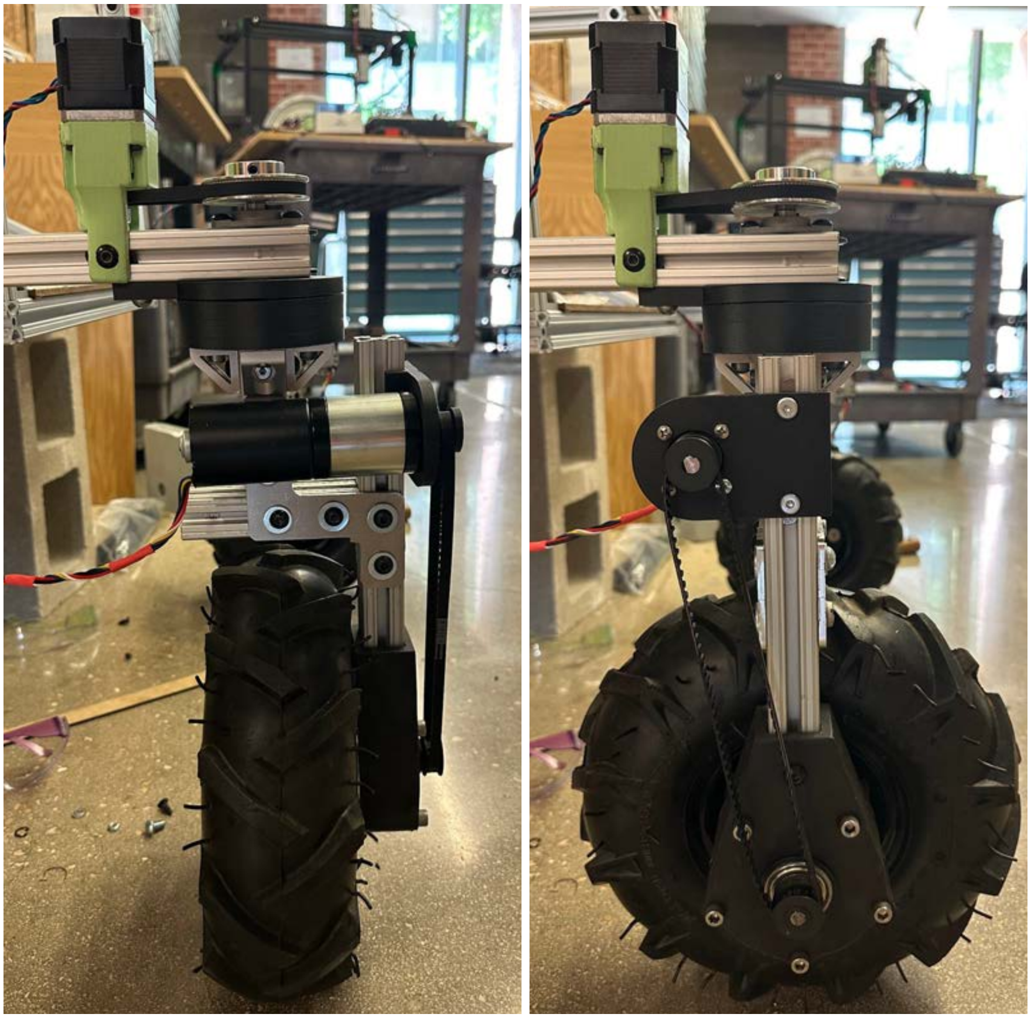

Figure 5: Fully Constructed Steering Column

Electronics

The rover's electronics subsystem is responsible for the control of and power distribution to each of the rover's motors. In the rover's original design, six individual motor drivers were used to control the rover's six independent brushless drive motors. These motor drivers were high-current, drawing up to 20 Amps each, and interfaced with an Espressif ESP8266 microcontroller using logic level shifters to step the ESP's 3.3V to the 5V required by the driver boards. The independent research student who worked on the rover's electronics in 2022 identified an alternative brushless motor with built-in drivers and a much lower current draw, and implemented two of them into the design. Our team built on this, ordering four more of these 12V motors, and interfacing them with a new ESP32-WROOM-02 development board. This new board was acquired to replace the old ESP8266 microcontroller because we needed more general purpose I/O pins to run the stepper motor drivers that would also be added into the design later. This new arrangement is lighter, has a smaller footprint within the chassis, and uses fewer wires than the old wiring harness and driver boards. Our team was also tasked with adding active steering to the design, so the integration of four stepper motors with 5:1 planetary gearboxes was carried out using four A4988 stepper motor driver boards. These boards allowed us to control each motor using only two signal pins, simplifying programming and wiring complexity significantly while ensuring the microcontroller is protected from back-EMF voltage spikes that can be caused by the stepper motor coils energizing. Geared stepper motors were chosen to steer the rover due to their high holding torque, precise positioning, and compact form factor. The designs for this can be seen in Figure G1 and Figure G2 in Appendix G.

This new electronics subsystem was implemented using a soldered perfboard, which hosted the four A4988 stepper motor driver boards and screw terminals for the stepper motor coils, drive motor power supply, and drive motor control pins. The screw terminals and underlying wiring weresized based on expected current draw, and the terminals were organized to align with the arrangement of the motors on the rover itself to avoid wiring overlap. The largest screw terminals delivered power directly to the motors, while more compact terminals were used for the low-current control pins of the brushless motors. The board takes in +12V direct-current power via two 10 AWG snap couplers. These wires split off into two 10 AWG power buses that deliver +12V directly to the six brushless motors. An LM7805 voltage regulator is used to provide a +5V direct-current rail that powers the A4988 driver boards and the ESP32 microcontroller. The schematic for this setup is shown in Figure G2, although pin numbering is not consistent with our final design, and this prototype schematic lacks the BJT current sink transistors that will be discussed later on in this section. The perfboard connects to the microcontroller via a 20-pin header that splits into female Dupont wires which connect to the proper GPIO pins on the microcontroller. Each Dupont wire has a piece of heat shrink with its number on it, allowing for easily documented management of the signal wires. We acquired a breakout board for the ESP32 microcontroller that allows for easy access to its GPIO pins and power rails. It also allows us to power the microcontroller using the power distribution perfboard's 20-pin connector[1].

There are two main types of output signal wires, *direction* and *speed*. Direction wires can be held either HIGH or LOW, and determine whether the stepper motors and drive motors turn clockwise or counterclockwise. Speed wires operate using PWM, or pulse-width modulation, a form of signal that rapidly oscillates HIGH and LOW to emulate an analog output, or a "partial" value. For instance, a speed wire that is HIGH half the time and LOW half the time would have a 50% duty cycle, and the resultant speed would be half of the maximum possible value for that motor. There is a direction and speed pin for each independent stepper motor, but only one direction and speed pin for each *side* of the rover. This is because there is no reason for the drive motors on one side of the rover to turn against each other or turn at different speeds, and as a result, we are able to save ten GPIO pins and further reduce wiring complexity. An important note about the speed pins on the brushless motors is that they are normally pulled HIGH to +5V, and as such will cause the motors to rotate if left floating or disconnected. To control them, a transistor must be used to sink current from the speed pin to GND (350mA max according to the datasheet). By activating 2N2222A NPN transistors using microcontroller I/O pins, these motor speed wires can be pulled LOW, causing the motor to stop. Similarly to the speed pins of the A4988 stepper motor drivers, the duty cycle of the PWM signal driving these NPN transistors determines the speed of the drive motors.

Twelve of the 20 pins are output signal wires, and two are used for the +5V rail and GND to power the microcontroller. This leaves six free pins, which were added to the design to support further expansion of the electronics subsystem. Namely, to support the inclusion of feedback input signals such as limit switches that can tell the rover to adjust its steering steppers if timing belt slippage causes them to turn too

[1] The pin mapping of this subsystem is available in the appendix under Table G1 with its associated color-coded wiring schematic in Figure G4.

far. If the steering assemblies turn too much in one direction, they would twist the drive motor wiring out of its terminals. Limit switches were acquired to signal the microcontroller when a wheel turns more than 90 degrees in either direction, and can also be used to “re-home” the wheels when the program begins by measuring the amount of steps required to reach either end of the revolution.

The microcontroller used in this project was programmed in C++, using Arduino libraries. The main program has two functions, *turn* and *drive*, which it will execute depending on the position of an analog joystick connected to the ADC pins of the microcontroller. This joystick allows us to easily “drive” the rover in real-time, and test its capabilities. The program uses simple *while* loops to call these functions based on the analog value of the two potentiometers in the joystick, passing the functions different *speed* and *direction* parameters. Versions of this program were created to drive the rover autonomously with a series of predetermined function calls, or using a wireless transmitter as proof of concepts, but the main program used for testing and control involves the wired analog joystick. This program can also display information on a laptop serial terminal about the rover’s current output state and analog control input values over a UART serial connection. The program utilizes a readable, organized scheme for defining pin numbers that helped immensely during the prototyping process. We learned that not all of the ESP32’s I/O pins can be fully utilized as GPIO outputs, as some of them natively control the microcontroller’s flash management system or serial communications lines. These pins would prevent the ESP32 from booting if anything was connected to them, or cause outputs to behave erratically during testing. Formatting the program this way and labeling our pin numbers allowed us to quickly switch over to pins that would not interfere with the ESP32’s hardware functionality.

Construction of the power distribution and control board for this subsystem required a perfboard, two 10-pin headers, twelve 3-and-4-pin screw terminal blocks, four A4988 stepper motor driver boards and associated pin headers for easy removal, two 2N2222A transistors, a LM7805 voltage regulator, a 20-pin ribbon connector, 20 Dupont wires, heat shrink tubing, eight brass board standoffs, and two 10 AWG snap connectors. This board was soldered with 16 AWG stranded copper wire for the lower-current power buses that powered the A4988 stepper motor drivers and microcontroller, and 26 AWG wire for the signal wires used to control each stepper driver. Wire strippers were used to prepare these wires for soldering, and crimpers were used to place the snap connectors on the 10 AWG power wires coming off of the board. A heat gun was used to place protective heat shrink tubing around wire extensions to each of the motors, as well as the solder joints on the 2N2222 transistors. These transistors had to be soldered to 3-pin headers for easy removal and so that they made firm contact with their 3-pin sockets. Heat shrink tubing was also used to tag each of the twenty Dupont signal wires going to the microcontroller with their documented number. The final construction setup and wiring mounted on the rover can be seen in Figs. 6-8.

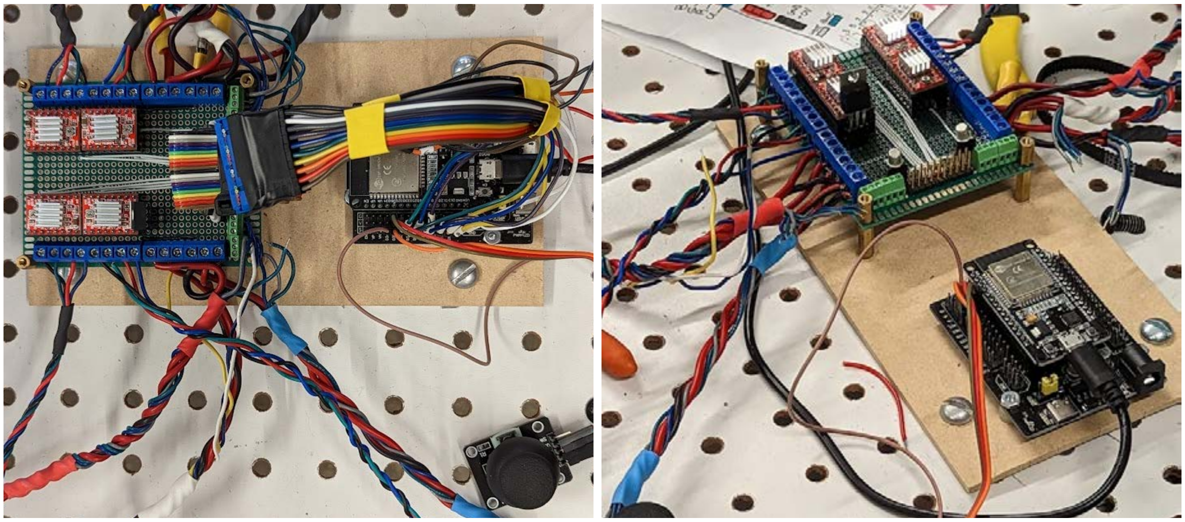

Figure 6: Full electrical subsystem with and without 20-pin ribbon connector installed

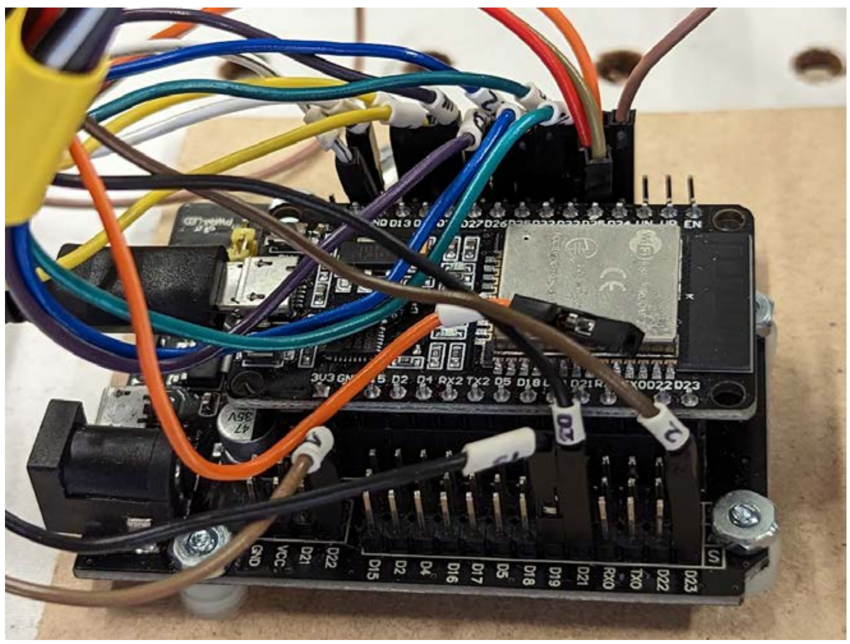

Figure 7: Labeled connections to ESP32 microcontroller breakout board

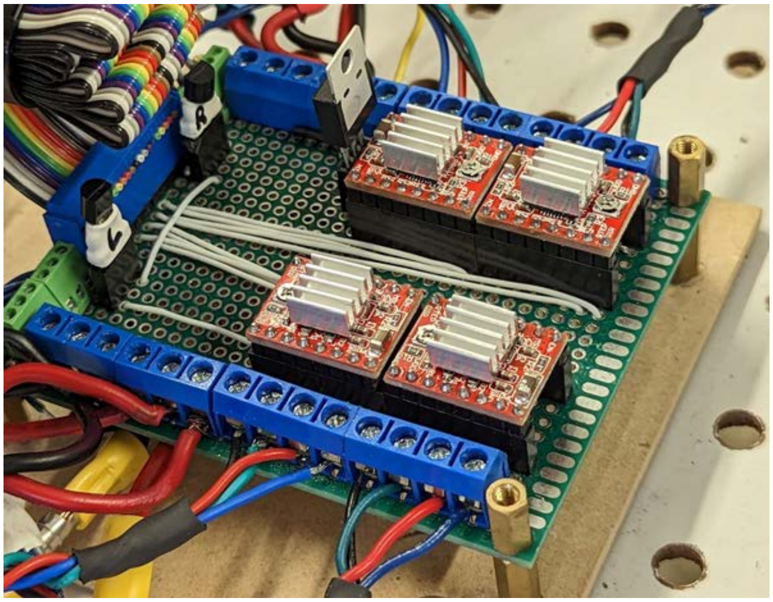

Figure 8: Soldered perfboard hosting stepper driver boards and motor signal wires

III. Design Evaluation

To verify if all project requirements, constraints, and standards were met by the team's rover design, we tested the rover using seven different tests that targeted both individual subsystems as well as the whole rover. The success or failures of each test led to additional improvements and iterations of the rover test. The following section summarizes each of our completed tests, as well as whether they demonstrated a successful completion of the stated requirements and constraints. In this section, we will be discussing each requirement thoroughly and include each relevant test. For tests which evaluate to multiple requirements, they will be discussed at length in the first requirement that they apply to and then mentioned again to discuss how they evaluated any further requirements.

1. Clearance

The distance maintained between the ground and underside of the Rover chassis shall be a minimum of 10.2 inches (the diameter of a wheel) in order to avoid any collisions between the chassis and obstacles.

Relevant Test: Clearance Capability Test

To test the rover's underbody clearance, we placed it on a flat surface over an obstacle of the height of the diameter of the wheel (10.2") with and without the 50lb battery weight applied to the chassis, such that the rover straddled the obstacle and all six wheels remained on the ground (this differed from the rover driving a wheel over the 5.1" obstacles).

Objective:

The objective of this test was to assess the suspension subsystem's ability to hold the rover chassis high enough to straddle obstacles 10.2" high without collisions with the obstacle, thus mimicking the need to drive over certain rocks and other obstacles when traversing difficult terrain in the field.

Features Evaluated:
This test specifically evaluated the chassis size and whether its underbody was far enough from the ground. It also evaluated the suspension system's ability to support the chassis off the ground with and without the battery load.

Test Scope:
The scope of this test was to test clearance capability by placing an object that was exactly 10.2 inches high to represent our required clearance height underneath the rover chassis with and without a load. This test involved only the underbody clearance dimension of the rover.

Test Plan:
Instruments/Tools and Setup: Instruments needed to construct the 10.2" obstacle included 5.25" by 5.25" column of wood, a ruler, and a vertical bandsaw. Once the obstacle was constructed, no instruments were needed to conduct the test with the rover. To set up the test, all six wheels of the rover had to be a flat surface, first without the battery load and second with the battery load. The obstacle was placed about one foot directly in front of the rover's path.

Assumptions: No assumptions were made.

Procedure: Once the rover and obstacle were set up, the rover was driven straight over the obstacle. To complete the test, the entire rover drove over the obstacle to make sure the entire underbody could clear the obstacle without collision.

Acceptance Criteria:
For this test to be deemed successful, the underbody of the rover had to completely clear the obstacle and have no contact with the 10.2" obstacle. Successful clearance was defined as not touching, dragging, or high-centering (teeter-tottering) on the obstacle.

Test Results:
The entire rover successfully drove over the obstacle during the trial with no collisions on the lowered chassis. The resulting pictures from this test can be found in Figure 9.

Evaluation:
Since the designated obstacle height was able to pass under without hitting or high-centering the rover, the results of this test met the acceptance criteria and the test was deemed successful. The overall design of the rover therefore meets the clearance design requirement. It was determined that there still remained about 3.625 inches between the lowest part of the chassis and the top of the obstacle. Therefore, future design iterations could include further reductions in the leg length and overall rover height.

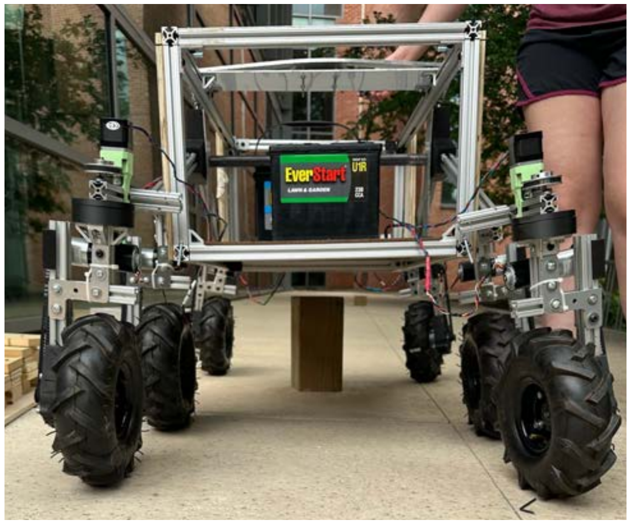

Figure 9: Clearance Capability Test setup with a 10.2" block representing the required clearance height

2. Dimensions

The Rover must be less than 98.3 inches in height and approximately 33.75 inches in width in order to fit through a standard door in CSI.

Relevant Test: CSI Door Dimension Test

To verify the dimensions of the rover could fit through a standard CSI door, the rover was driven through a CSI door with all mounted components (motors, gearboxes, pulleys, etc.).

Objective:
The objective of this test was to confirm that the entire rover, once fully built, could enter/exit through a standard CSI door.

Features Evaluated:
The main feature being evaluated was the overall size of the rover. Individual features that are part of the overall size include the width of the suspension system, the size of the chassis, the width of the steering columns with attached motors, gearboxes, and wheels, and mounted electronics on the exterior. Each of these components sat off of the main chassis, and therefore introduced possible interference with the width of a CSI door.

Test Scope:
The scope of this test required a fully intact, standing, and mobile rover to be placed in or driven through a standard CSI door. The width dimension was the main focus of this test.

Test Plan:
Instruments/Tools and Setup: Besides the rover itself, no instrumentation was required to conduct this test since the CSI door functioned as the measuring tool for overall width of the rover. To set up, the rover

was placed in front of a standard CSI door, and it was verified that all wheels were facing straight and all pulleys were tightened.
Assumptions: The assumption made for this test is that all doors in the CSI are a standard size, and therefore the team could test on one CSI door with the idea that if the rover passed the test, it could drive through any door in the CSI, including the lab where it is stored and the Makerspace where it was built.
Procedure: Once the rover was positioned directly in front of the CSI door, it was driven straight forward until it completely passed through the doorway, ensuring every part of the rover could fit through the door.

Acceptance Criteria:
The results of this test were considered a success if the rover could fit through the CSI door without collisions with the sides of the door frame or damaging/removing any components of the chassis, steering system, or suspension system.

Test Results:
The rover was driven completely through the door without any components colliding with the door frame or opened door, as seen in Figure 10. The rover was moved very slowly to avoid side-to-side rocking into the door frame.

Evaluation:
Due to the instability of the legs, the rover tended to lean to one side while moving. Therefore, when this test was conducted, the movement of the rover had to be very slow to avoid the side-to-side rocking movement that would cause the steering assemblies to run into the frame. Besides the slow movement, the rover successfully drove through the doorway without collisions, which means it met the acceptance criteria for the dimensions design requirement.While the test was successful, there was less than an inch between the pulleys mounted on the gearboxes and the edge of the doorframe. Therefore, the overall width of the rover cannot not be increased in any future designs. Possible methods to reduce the closeness of the width dimensions to the door dimensions would be to reduce the overall width of the chassis, thus bringing the suspension and steering systems in away from the edges of the door. Another method to address adjustments to the width of the rover would be to rotate the gearboxes inside to avoid any collisions with the pulley system.

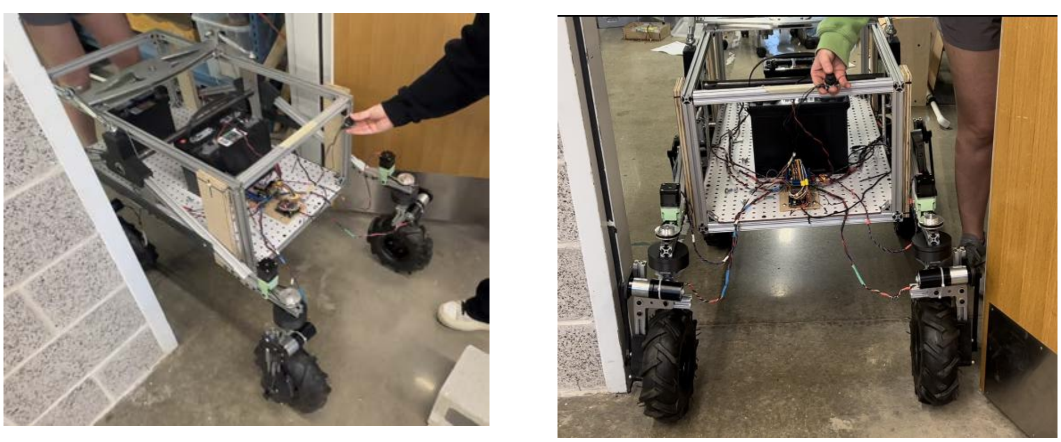

Figure 10: Successful CSI Door Test

3. Steering

The Rover must have an active steering system capable of achieving a minimum turning radius of 12 inches with no wheel slip against the ground.

Relevant Test: Steering Torque Test

This test was performed during the Fall semester and determined the amount of torque required to turn each wheel of the rover when subjected to several loading conditions, allowing the team to accurately size our steering motors.

Objective:
The objective of this test was to use a mockup of the rover's steering column assembly to determine the required amount of torque needed to turn the wheel on a standard CSI tiled floor in order to dictate which size steering motors to purchase.

Features Evaluated:
This test evaluated our design for the rover's independent steering subsystem, specifically the steering motor required to turn the individual steering columns.

Test Scope:
This scope of this test examined the amount of torque required to rotate the steering column assembly with incremental loads provided by objects available in the lab (Cinder blocks and water jugs). The load increments tested were 28.75 lbs, 37.25 lbs, 57.5 lbs, and 79.25 lbs. These increments were all different due to the objects being used to load the steering column, but demonstrated the behavior of the column around and above our expected load of 30 lbs on every steering column. Since all conditions exceeded our estimated load of 30 lbs on each steering column when the total load is distributed evenly, the test provided a worst-case estimate of the required torque for the steering motors. The amount of torque required to turn the steering column assembly was the only variable tested.

Test Plan:
Instruments/Tools and Setup: This test required wood, screws, a drill, and a Wera Torque Screwdriver. To set up this test, a wooden support was constructed using hardware and wooden blocks from the Makerspace. This structure consisted of two legs and a top piece with a hole. Setup required placing the steering column in the hole such that the entire assembly was supported in a standing position, with the wheel touching the ground and the 80/20 aluminum column protruding above the wooden stand (See Figure 11). A wooden plank was then attached to the top of the 80/20 steering column via a screw to provide a platform for the loads to be placed.

Assumptions: We assumed that all six wheels on the rover would carry the same amount of weight and therefore all four wheels with steering motors would require the same amount of steering torque.

Procedure: A screw was inserted into the center of the wooden sheet, and the Wera torque screwdriver was used with the screw to turn the steering column assembly. The torque screwdriver is designed to be set at certain torque values such that when that value is reached, the screwdriver fails. With this setup and the reading from the torque screwdriver, we were able to develop an idea of how much torque is required to turn the wheel under several different loading situations, which then allowed us to size our steering motors. The screwdriver was used at least twice for each variable load to verify the torque measurement.

Acceptance Criteria:

This test was deemed successful if the team was able to obtain repeatable and verifiable torque measurements that could provide a useful reference when sizing our steering stepper motors using their holding torque ratings. The holding torque ratings were used as the defining factor since we expect holding torque to be the highest required torque from the steering motors.

Test Results:

With the lowest torque setting being 1.2 Nm on the Wera screwdriver, 1.2 Nm was the team's reference value. The wheel and steering assembly could be turned at the 1.2 Nm setting without the screwdriver failing while carrying loads that varied from ~28 lbs to ~59 lbs and only required 1.7 Nm for the load of ~79 lbs.

Evaluation:

Since all loads overestimated the expected loads and all of the stepper motor candidates for the steering motor had holding torques at or above 1.2 Nm, the team deemed the test successful. This information was used to inform the team's purchase of the 5:1 Planetary Gearbox Nema 17 Stepper Motor.

Figure 11: Steering Torque Test Setup

Relevant Test: Steering Motor Assembly

This test focused on turning a single steering column 90 degrees while under a 30 pound load using the chosen stepper motor to simulate the behavior needed from the motor to execute steering maneuvers.

Objective:
The objective of this test was to verify that the stepper motor belt pulley system used is capable of turning the motor, gearbox, wheel, and leg assembly 90 degrees while under one sixth of the total weight of the rover and the additional 100-pound load, which we have estimated to be about 25lbs.

Features Evaluated:
This test evaluated the rover's steering subsystem, specifically the performance of the stepper motor and belt pulley system as seen in Figure E9, while also evaluating the functionality of the electronic circuitry driving the stepper motor.

Test Scope:
The scope of this test was to make sure that the steering motor produced enough torque to turn the steering columns, and not on interfacing the steering system to the rover. The motor being tested was a 5:1 Planetary Gearbox Nema 17 Stepper Motor. As seen in Figure E9, the motor was mounted on a horizontal member of 80/20 connected to the vertical steering column using a 8 mm aluminum shaft through two 8mm flanged bearings and a timing pulley.

Test Plan:
Instruments/Tools and Setup: The setup for this test consisted of clamping the horizontal piece of 80/20 to a table to keep it stable, and then running a code to turn the motor (Fig. 12). NEMA ICS 16 was used as a reference to ensure the stepper motor was used within its ratings.

Assumptions: We assumed that all six wheels on the rover would carry the same amount of weight and therefore all four wheels with steering motors would require the same amount of steering torque to turn.

Procedure: To execute the steering prototype testing plan we designed and constructed one fully functional steering column using the proposed stepper motor belt pulley system. This steering column was mounted to a table or some other structure for support so that we could analyze the stepper motor belt pulley system's ability to rotate it. The steering column was loaded with one sixth of the total expected weight of the rover (including the 100 pound load) to simulate what a single column would carry under equal load distribution across all six steering columns. The stepper motor was programmed to turn the column 90 degrees while loaded.

Acceptance Criteria:
For our steering prototype test to meet the acceptance criteria, the stepper motor belt pulley system had to rotate a 30lb loaded steering column assembly at least 90 degrees without damaging the stepper motor or breaking the pulley. The test had to also be performed without blowing the circuit board and controller being used to control the motor or blow the motor itself.

Test Results:
After conducting the preliminary steering subsystem test we found that the selected steering motor was unable to produce an adequate amount of torque to rotate a steering column loaded with 25lbs. The stepper motor functioned correctly while the steering motor was unloaded, with the steering column spinning in a full 360 degree turn, but once load was added, no turning motion could be achieved. A second iteration of the test was conducted after making improvements to the system, which included

installing a larger pulley with 80 teeth instead of 60 teeth and changing some of the wiring in the motor circuit. During this test, the same stepper motor was able to turn a steering column loaded with 25lbs 90°. The turn itself was very slow, but the movement of the wheel was consistent and the motor did not fail or catch.

Evaluation:
Due to the fact that the steering motor was unable to rotate the weighted steering column assembly, the initial iteration of this test was a failure. While investigating this issue with the sponsor, the team designated several areas of possible problems: the electronics setup, the slippery CSI floor, a malfunction in how the motor activates, and a gear ratio in the stepper motor that is too small. The team did find that the steering motor was receiving less than half of its rated current when attempting to turn the loaded steering column, so we focused on changing the electronics setup and circuitry to address this issue, while also upgrading the size of the pulley placed over the steering column to improve the gear ratio and to demand less torque from the stepper motor.

Since there are no speed requirements in the scope of this project or test, we deemed this test successful. Furthermore, the circuit board, controller, and motor all remained intact with no shorts, burn outs, or any other damage, verifying our current electronic setup for the steering motor.

Figure 12: Final steering motor assembly test setup

Relevant Test: Turning Radius Test

Following the full implementation of the rover's steering system, this test determined the rover's minimum turning radius of the rover when all four steering columns were engaged in a turning maneuver.

Objective:

The objective of this test was to verify that the rover's steering subsystem is capable of achieving a minimum turning radius of 12 inches.

Features Evaluated:

This test evaluated the rover's active steering subsystem which consists of four steering steering motors, and six driving motors, and how these two motor types worked together.

Test Scope:

Given the simplicity of this test, the test scope was simply to drive the rover in a circle and measure the radius of the turn. To be sure that we obtained repeatable data, we tested the rover's turning radius for both left and right-hand turns.

Test Plan:

Instruments/Tools and Setup: To set up this test, we placed the rover in an open area and pre-set the wheels in a turned position so that once it began moving it started to turn.

Assumptions: No assumptions were made for this test.

Procedure: After placing the wheels in their respective turning positions and turning on the rover's electronics system, we then used its joystick to turn on the driving motors. In theory this would allow us to begin driving the rover in a full circle in a way that would allow us to measure its turning radius.

Acceptance Criteria:

To meet the acceptance criteria for the turning radius tests, the rover must complete 3 turns with a turning radius less than or equal to 12 inches. Specific to our test, this means that it must complete the turns without breaking/disconnecting the 12-inch string connected to the center of the turn. If this is achieved then it means that the rover's turning radius meets the project requirements.

Test Results:

Due to the rover's instability issues it was unable to produce a measurable turning radius. The rover's independent steering system includes wheels that can rotate a full 360 degrees, theoretically giving it a turning radius of zero. However, due to f its overall instability and unreliable driving motor setup, it was unable to complete the turn. Without a full turn we were unable to record the rover's turning radius, therefore resulting in a failure for this test.

Evaluation:

This test's failure to achieve the turning radius requirement can be attributed to the overarching stability issues caused by the weak 1 inch aluminum 80/20 used in the rover's legs and suspension system. During this test, the team was able to observe excessive torsional deformation in the longest 80/20 suspension members protruding from the nylon rocker joint. This torsional deformation can be observed in Fig. 13.

Unfortunately, this issue was not observable until the final week of testing during the course of the project, as other more prevalent issues had to be fixed before the full rover prototype could be retested. The team has attributed the main source of this torsional deformation to the weakness of the 80/20 used on the suspension.

While we did not have sufficient time to solve this problem, our recommendation to future groups looking to address this problem would be to select a stronger material for these load bearing members such as 1 inch steel square tubing or thicker aluminum bars. Through testing and observation, our group determined that this material weakness is the primary source of the problem, and we believe that a simple change in materials would solve the issue and allow the rover to complete this project requirement. This deformation must be addressed going forward before the current steering system can be fully tested if the rover is to successfully meet the turning radius requirement.

Figure 13. Observable torsional deformation in 80/20 suspension members experienced during tests

4. Suspension

The Rover's suspension system was upgraded to be more robust, while still able to interface with the active steering system to maneuver around and over obstacles.

Relevant Test: Suspension Joint Stress Test

The first test of the rocker-bogie suspension was performed during the fall semester and used mathematical analysis and Fusion 360 to verify our design's ability to support the static stress of the rover's weight and 100 lb load.

Objective:

The objective of this test was to evaluate the durability of our proposed rocker-bogie suspension setup by determining if our design could withstand the expected static load from the weight of the rover and its carrying capacity.

Features Evaluated:
This test focused on the rocker-bogie suspension system. Specifically, this test evaluated the strength of the 80/20 aluminum extrusions in our suspension configuration and the strength of the current 3D-printed nylon joints used to connect mechanical members.

Test Scope:
The scope of this test consists of two parts: a mathematical analysis and Fusion 360 stress analysis examining the internal forces on various rover parts when it is loaded to the 100 lb requirement.

Test Plan:
Instruments/Tools and Setup: The mathematical analysis involved formulating force body diagrams of the rover while sitting still on flat ground and solving for the expected axial and shear stresses on each of the mechanical members. Fusion 360 was then used to model our suspension design and perform a stress analysis on the 127-degree joint connection we expect to have the largest percentage of the total load. The forces applied in the Fusion 360 simulations were determined by our mathematical analysis.

Assumptions: When conducting this test, we assumed that each joint for all six wheels would be supporting the same amount of weight and that when at rest, the force acting downwards on both sides of the rover was symmetrical. The total load of the rover (weight and carrying capacity) is distributed evenly between the right and left sides of the rover. Therefore the right and left sides of the suspension each hold half the total load. We then focused on only one side of the suspension (6 members) and used half the total load as our static load. We also assumed that the bogie and rocker components of the suspension are two rigid bodies connected at a pin joint with equal and opposite forces applied by each component.

Procedure: Once the team had developed a rocker bogie design that could satisfy both the suspension and steering requirements, we determined that to use steering columns we needed six mechanical members with 90-degree connections on the bogie, and custom 127-degree, 98-degree, and 45-degree connections between the other members of the rocker. We then used our known dimensions of the rover that fit within our dimensions requirement and calculated the subsequent lengths of each member and angles in between each of the connections. Following these calculations we performed a static analysis on the suspension. Once the forces on each mechanical member were calculated, the axial and shear stresses in each member was calculated with a safety factor of 3. The calculated stresses were then compared to the yield stress of the 80/20 extruded aluminum being used to make the members. This comparison determined whether or not the suspension members were anywhere close to yield under static loads.

The next step was to stress test our model of the rocker-bogie design in Fusion 360. Working off of the rover model with the newly designed rocker-bogie components, a mockup of a differential bar and custom joints were printed using composite nylon material. We used the stress analysis feature in Fusion 360 to assess the stress put on the 127-degree joint, which we expected to be the joint with the highest percentage of the total load. Given our expected stresses on each member from the mathematical analysis, the Fusion 360 stress analysis gave us an idea of whether or not the composite nylon material used for connections in the rocker bogie design can withstand the obstacle course at the end of the spring semester, and whether an alternative material, aluminum, showed greater strength under the same stress.

Acceptance Criteria:
The mathematical calculations and statics analysis were deemed successful if the forces for every member were calculated to completion and resulting stresses demonstrated yield was not reached in any of the 80/20 members (even with a safety factor of 3.0). The stress analysis test was determined to be successful if the measurements taken by Fusion 360 showed that the calculated stress applied on the 127-degree joint was less than that required stress to deform or break our proposed joint design, as well as if it showed a visible difference in strength between composite nylon and aluminum.

Test Results:
Since all calculated stresses were far below the yield stress of 80/20 aluminum when calculated with our determined safety factor of 3.0, the first part of the test demonstrated the members would not bend and was deemed successful. The stress analysis was deemed successful since it showed the points of stress on the joint with the expected forces, as well as demonstrated a noticeable difference between composite nylon and aluminum materials. The results of this test can be found in Figures C3 & C4 in Appendix C.

Evaluation:
While the results of this test did not confirm whether switching away from nylon was a must, they did demonstrate a possible weakness in the connection between the joint and the 80/20 that the team must look for moving forward. However, the team determined that the small difference between the aluminum and nylon joints was not significant enough to warrant changing the current design, and thus we chose to stick with 3-D printed nylon composite joints.

Relevant Test: Suspension Differential Bar and Tipping
We tested our implementation of the rocker-bogie suspension differential bar by assessing the angle of tilt of the chassis while the rover was on top of a 5.1-inch obstacle.

Objective:
The objectives of this test include verifying that the chassis is not exceeding the 20° and 30° average roll and pitch angles when traversing obstacles, as well as ensuring that the rover does not tip over.

Features Evaluated:
This test evaluated the suspension subsystem differential bar, which enables the two sides of the suspension to move independently. The differential bar was evaluated based on the angle of tilt of the chassis when one side of the suspension was raised on an obstacle. This test also provided a visual/observational test to see if the mechanical members or joints were fracturing or bending.

Test Scope:
This test examined the functionality of the differential bar under static conditions while the rover was sitting on an obstacle.

Test Plan:
<u>*Instruments/Tools and Setup:*</u> To measure the angle of the chassis, a level was used. Angle measurements gave the team an idea of how far the rover tipped when traversing over the highest obstacle in the obstacle course, allowing the team to make adjustments to the differential bar if needed. Placing the rover in the

static position of one side on an obstacle and the other side flat also gave the team a visual of how mechanical members and joints are behaving. As far as instrumentation goes, the only instrument used for this test was a level. A 5.1 inch obstacle was constructed from wood to be used for this test

Assumptions: For this test we assumed that the other wheels would be flat on the ground while one of them would be placed on a 5.1 inch obstacle.

Procedure: For this test, one of the rover's wheels was placed onto the 5.1" obstacle from the obstacle course, and the chassis pitch and yaw angles were recorded using a level. This process was repeated until every wheel had its turn being placed on the obstacle. The rover was planned to carry a 100lb load during the whole test, however due to stability issues this test was done with no load. We used a level to take manual angle measurements. The team also performed a visual inspection of the mechanical members and suspension joints during each position of the rover to ensure no bending or fracturing.

Acceptance Criteria:

The chassis stability test results were accepted if the average pitch and roll angles output by the level did not exceed limits of 20° and 30° respectively while each of the wheels on one side of the rover were atop the 5.1" obstacle. The angle of the chassis while the rover is on level ground was recorded as a basis for comparison for the tilting angles. Visual inspection of the suspension members and joints were successful if the team did not detect any bending or fracturing.

Test Results

As illustrated in Tables 1 and 2 and Figure 14, this test was considered a success because every recorded angle fell under the 20° and 30° roll and pitch limits identified by our test plan. For the first trial, the original roll and pitch measurements were 0° and 3° respectively, so all numbers in Table 1 demonstrate the angle value adjusted for the original angle of the chassis. After shortening the overall leg lengths, this test was performed a second time. The original roll and pitch measurement for the second trial were both 0°, and thus Table 2 demonstrates the measurements taken during the trial with no need for adjustment.

Table 1: First Trial Adjusted Differential Bar and Tipping Test Results

	Front Left Wheel	Front Right Wheel	Middle Left Wheel	Middle Right Wheel	Back Left Wheel	Back Right Wheel
Pitch (deg)	6	1	1	0	0	1
Roll (deg)	4	5	2	1	1	2

Table 2: Second Trial Differential Bar and Tipping Test Results

	Front Left Wheel	Front Right Wheel	Middle Left Wheel	Middle Right Wheel	Back Left Wheel	Back Right Wheel
Pitch (deg)	3	4	1	2	1	3
Roll (deg)	3	5	1	4	1	4

Evaluation
With all measurements below our set limits, we were able to demonstrate that the rocker bogie was functioning properly and was keeping the chassis stable while the obstacle was under each of the six wheels, mimicking several different obstacle configurations. Visually, the team did observe bending in the bogie joints, specifically with the right side bogie bending outward and the left side bogie bending inward. While we still deem this test a success because no fracturing occurred in the beams, it did pinpoint key areas of weakness that the team must address moving forward. It was due to this bending that the team did not feel confident the rover could support a full 100-lb load yet, and thus the test was performed with no load. Nonetheless, it was successful in demonstrating that our differential bar was functioning properly.

Figure 14: Differential Bar and Tipping Test Setup

Relevant Test: Obstacle Course

Following the testing of all individual subsystems, the final rover prototype will be put through an obstacle course designed by the group to test the rover's performance and verify all project requirements have been met.

Objectives:

The obstacle course test is the main evaluation of the rover's performance. The rover's completion of the obstacle course with a rocker-bogie suspension and an active steering system while carrying 100 pounds of extra weight will fulfill the requirements of the project. This test will follow the subsystem tests and aims to assess how well the subsystems work together to maneuver the rover over and around various obstacles. The obstacle course test will ensure that the requirements regarding steering, suspension, carrying capacity, and ability of the rover to climb over obstacles are met with the final prototype design. Specific objectives include:

1. The rover can steer around turns or large obstacles with a turning radius of 12" or less.
2. The rover can traverse over obstacles 5.1" tall or less with the rocker-bogie suspension, without tipping over and while not exceeding average pitch and yaw angle limits of 20° and 30° for the chassis.
3. The rover can complete the course with a 100-pound carrying capacity
4. The rover can be driven electronically, either through a programmed and loaded code or a remote control.

Features Evaluated:

This test evaluated the rover as a whole, the cohesiveness of the subsystems, and the success of the implemented robust suspension and active steering systems to fulfill the project requirements. This test also verified that the NEMA ICS 16 and SAE J3206 standards (Appendix B) were followed and that the team implemented safety protocols for our driving system and stepper motors correctly. The team's maintenance and servicing (charging) of the lead-acid battery used for each obstacle course test was dictated by SAE J2950 (Appendix B) and evaluated during the obstacle course by observing the overall performance of the battery while the rover was driving all 10 motors.

Test Scope:

Since all subsystems had been individually tested, the obstacle course tested the rover prototype as a whole by running the rover through an obstacle course. This test required the construction of obstacles and the obstacle course itself. The obstacle course was constructed and completed with various sized/shaped obstacles, with one type of obstacle that was 5.1" high, one type of obstacle that was 10.2" high, and terrain that was different, uneven heights (with a maximum height of 5.1"), as well as turns that required a 12-inch turning radius. Since the rover was driven via a loaded program, the team also monitored the safety of the equipment, the rover, and themselves per the SAE J3206 standard, ensuring that this standard was being followed. Finally, since the rover utilized 4 stepper motors, the team followed NEMA ICS 16 (Appendix B) and monitored the power intake and feedback from the stepper motors throughout the test to ensure the motors were being used within their ratings.

Test Plan:

Instruments/Tools and Setup:

To execute that test, the team first developed an obstacle course design that consisted of turns, obstructions, and pathways with different terrain heights. The turns required a turning radius of 12” or less for the rover to stay within the course. The obstructions had a specific height of 5.1 inches (radius of the wheel) and 10.2 inches (diameter of the wheel). To fully test the suspension, there was also a section of the obstacle course that had a path with different heights on one side of the suspension, requiring the differential bar in the suspension to compensate for the height difference. The equipment needed to construct this obstacle course came from Trinity University Makerspace. The course itself had boundaries defined by tape, which was also used to denote where the rover turned. Equipment needed to construct the obstacles included screwdrivers, wood screws, and plywood. These were used to make blocks/cubes of various heights to serve as obstacles. Stacked sheets of plywood were used to create the different heights of terrain.

Assumptions: This test assumed that all subsystems would be functioning as intended, and that all other project requirements were able to be met.

Procedure:

Once the obstacle course had been constructed and the obstacles had each been placed in a designated location, the rover was moved through the obstacle course by a team member using a joystick to control the direction of the rover. Each run of the obstacle course required the rover to drive over two obstacles that were 5.1” or less, straddle two obstacles 10.2” high, turn two corners with a 12-inch turn radius, and drive over an uneven terrain path. The rover ran the same path through the obstacle course 3 times to verify that the suspension and steering could withstand repeated use. The constructed obstacle course along with the path of the rover is pictured in Figure 15, with an example of the uneven terrain path in Figure 16.

Acceptance Criteria:

Observations of how the rover traversed the different sets of obstacles determined the success of the design. Success was achieved if the rover drove over 5.1” obstacles without falling over, straddled a 10.2” obstacle without hitting the underside carriage or high centering, conducted turns with a 12” turn radius (measured using measuring tape) or less, and drove over uneven terrain (incremental height up to roughly 6 inches) without tipping (Fig. 16), falling, breaking, or causing the battery to slip off the chassis. It was verified before the obstacle course test that the 5.1” obstacles would not cause pitch and roll angles that exceeded the 20 and 30-degree constraints, so this was no longer a concern during this test. Visual inspections of tipping, deformation, and overall ability to climb and traverse obstacles were made to determine the success of the test. Success was determined if the rover could drive over the obstacle, solely powered by its battery and controlled by a joystick and with no help from the team, and with no destruction or deformation of the rover itself.

Test Results:

This test resulted in a fail. The rover was unable to traverse over any obstacles and complete turns, meaning that it was unable to perform the obstacle course in its entirety. While it was able to satisfy the underbody clearance and did not fully tip over at any point, it was unable to accomplish all other requirements given by this test. Additionally, our visual inspection was able to identify significant torsional deformation in the 80/20 lengths protruding from the rover's nylon rocker joint. For these reasons, this test was a failure.

Evaluation:
Based on the test results outlined above, our design was unable to meet several project requirements due to the instability of the rover as a whole. The severe lean experienced by the rover exacerbated any side to side movements and any difference in heights between the two sides of the suspension, threatening to tip the rover over. Furthermore, the steering columns were too weak to push the wheels over an obstacle larger than 0.5". The inability of the rover to complete the obstacle course led the group to identifying issues in the driving motor setup, the steering motor setup, and the nylon rocker joint, all of which have the potential to further improve the rover's performance by improving its stability. The driving motor setup which was provided to our group by the previous summer researcher was inadequate when implemented on the full scale rover. During dynamic loading conditions, the small 3D printed pulleys used in the drive motor's belt pulley system would detach themselves from the motor shafts on occasion.

In conjunction with slipping pulleys, the gearboxes themselves caused the wheels to bow inward, contributing to further slipping of the pulleys. Additionally, the nylon motor mounts used to hold the drive motors in place were held in place using just 2 80/20 screws and T-nuts. This attachment was insufficient to hold the motor in place while the belt was under the tension required to power the motor. Because of this, after a few seconds of driving the motor mount would slip and the belts would lose tension, causing them to slip and skip. Our recommendation to resolve this issue would be to order metal pulleys as opposed to the 3D printed ones currently used, and to redesign the motor mounts to be more secure and to be made out of aluminum as opposed to nylon. Next, our group observed some minor issues with the steering motor setup. Because the pulley and shaft flange used to transfer torque from the stepper motor to the steering columns are connected using just set screws, we noticed that the set screws would loosen over time, resulting in slipping. This is also a rather simple fix, and we recommend that a future group use partially keyed shafts in conjunction with keyed gears and keyed shaft flanges to ensure that the stepper motors can transfer their full power to rotating the steering column assembly. Lastly, our team also identified some issues in the main nylon rocker joint used in the suspension setup. For this, we recommend that future groups remake this joint, or a similar one, using aluminum to reduce any bending which may occur in the joint itself. If addressed, we believe that these recommendations would allow the rover to fully meet all of its project requirements by following all of the same testing procedures outlined in this document. If these issues were to be addressed, the obstacle course test could be repeated to evaluate the success of the design.

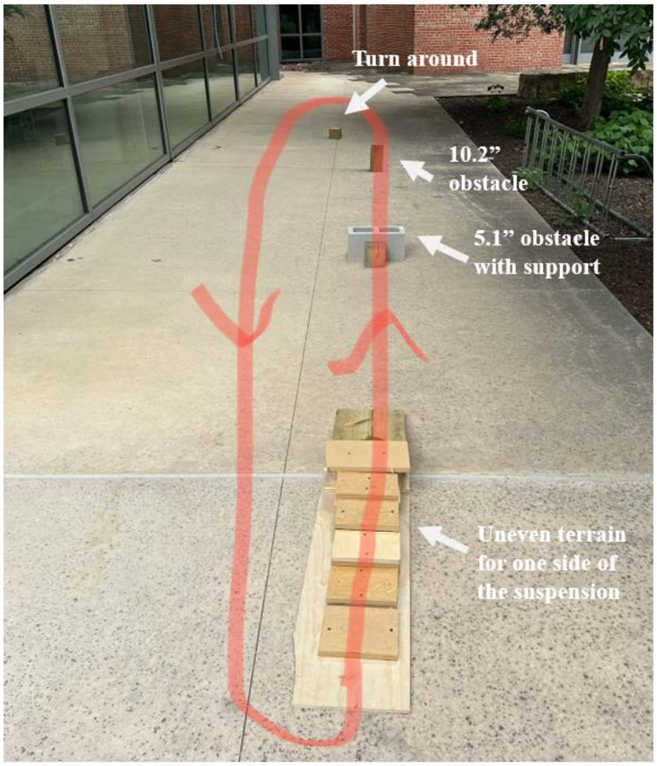

Figure 15: Obstacle course setup and rover path

Figure 16: Rover placed on the “uneven terrain” obstacle in the obstacle course

5. Ability to Overcome Obstacles

Both the left and right sides of the Rover's suspension must be able to independently traverse over obstacles with a maximum height of 5.1 inches without the Rover tipping over or getting stuck.

The following subsections detail the relevant test results, and evaluation for the Carrying Capacity requirement in tests that have been discussed in previous sections.

Relevant Test: Obstacle Course

Reference Section 4 under the Obstacle Course Test subsection for the **Objective, Test Scope, Test Plan, and Acceptance Criteria.**

Test Results (for overcoming obstacles during the obstacle course):

The rover was unable to traverse over any obstacle during the obstacle course. Any contact between the rover wheels and a 5.1" obstacle led to the rotation of the wheel, the slipping of the pulley, or the severe bending of the 80/20 members causing the rover to tip.

Evaluation (for overcoming obstacles during the obstacle course):

Since the rover was unable to overcome any 5.1" obstacles while moving through the obstacle course, it failed to complete this requirement. The rover did not tip because it was on the obstacles, but rather because of the torsional bending in the 80/20 members. The rover did however get stuck when it hit the obstacle, causing all steering columns to bend against the resistance of the obstacle and stall any forward movement.

Recommendations for improving the rover's ability to hit and drive over the obstacle are to improve the thickness of the steering shaft inside the steering column assembly. This shaft did not contain any grooves for the set screws and also had a very small diameter. This combination led to the steering column being unable to overcome the friction of pushing against the obstacle in an attempt to drive over it, causing it to turn as the rover attempted to drive forward. It is also recommended to use metal pulleys for the timing belts since the belts would begin to slip as the stuck wheel attempted to drive forward against the obstacle.

Relevant Test: Suspension Differential Bar and Tipping

Reference Section 4 under the Suspension Differential Bar and Tipping Test subsection for the **Objective, Test Scope, Test Plan, and Acceptance Criteria.**

Test Results (for overcoming obstacles during the tipping test):

Tables 1 and 2 demonstrate the measured angles Pitch and Roll directions in degrees for when the rover was placed on top of the 5.1" obstacle. Attempts at driving the rover at the obstacle led to the wheel getting stuck, making the rover unable to drive up onto the obstacle.

Evaluation (for overcoming obstacles during the tipping test):

All angles in Tables 1 and 2 are well below the 20 and 30 degree specifications while each wheel of the rover was placed on a 5.1" obstacle. However, these angles were achieved by placing each wheel on the obstacle rather than the rover itself traversing over the obstacle. Therefore, this requirement is partially met during this test. The rover does not tip when it is on top of this obstacle, giving the test some success for overcoming obstacles. The failure occurs when the rover is unable to drive over the obstacle without getting the tire stuck in place. This test is a partial success. The same recommendations for improving the steering shaft and pulley system, as stated previously, would help address this partial failure for future tests attempting to overcome obstacles.

6. Carrying Capacity

Since this project is inspired by planetary rovers that carry loads with experimental equipment and data samples, the rover must haul its own weight, plus an additional 100 pounds.

The following subsections detail the relevant acceptance criteria, test results, and evaluation for the Carrying Capacity requirement in tests that have been discussed in previous sections.

Relevant Test: Obstacle Course Test

Reference Section 4 under the Obstacle Course Test subsection for the **Objective, Test Scope, and Test Plan.**

Acceptance Criteria (for carrying capacity during the obstacle course):
The rover completes the obstacle course with an additional 100 lb load on top of the battery load.

Test Results (for carrying capacity during the obstacle course):
The rover was unable to complete the obstacle course with a 100 lb load due to instability in the legs. It attempted the obstacles only with the load of the 50 lb battery and a 15lb counterweight to keep the chassis straight.

Evaluation (for carrying capacity during the obstacle course):
Due to the torquing rotation in the 80/20 members of the rocker bogie, the rover failed to meet the carrying capacity requirement while conducting the obstacle course test. It was only able to reach 15 lbs of additional weight after the battery was placed in the chassis. Because the team observed such severe bending and in the rover legs when the 100 lb load was added, we decided to attempt to complete the obstacle course requirement while failing the carrying capacity requirement. As has been stated previously, improvements to the stability of the rover by changing the material of the legs to thicker 80/20 members or a different material entirely is recommended before future testing with a 100 lb load.

Relevant Test: Suspension Differential Bar and Tipping

Reference Section 4 under the Suspension Differential Bar and Tipping Test subsection for the **Objective, Test Scope, and Test Plan.**

Acceptance Criteria (for carrying capacity during the tipping test):
The rover completes the tipping test with an additional 100 lb load on top of the battery load.

Test Results (for carrying capacity during the tipping test):
The rover failed the carrying capacity requirement during this test because it was unable to support 100 lbs while on a 5.1” obstacle. Only the load of the battery and counterweight were used in order to conduct this test.

Evaluation (for carrying capacity during the tipping test):

The rover was unable to perform this test on the 5.1” obstacle while holding an additional 100 lb load. The additional load caused such severe bending in the steering connections that the rover would have toppled if placed on top of a 5.1” obstacle. Therefore, it had to complete the test with only the load of the battery and a 15 lb counterweight. As has been stated previously, improvements to the stability of the rover by changing the material of the legs to thicker 80/20 members or a different material entirely is recommended before future testing with a 100 lb load.

Relevant Test: Turning Radius Test

Reference Section 3 under the Turning Radius Test subsection for the **Objective, Test Scope, Test Plan, and Acceptance Criteria.**

Acceptance Criteria (for carrying capacity during the turning radius test):
The rover completes the turn radius test with an additional 100 lb load on top of the battery load.

Test Results (for carrying capacity during the turning radius test):
The rover failed the carrying capacity test with an additional 100 lb load because it was unable to support the 100 lb load while moving without tipping over. It attempted the test only with the battery load and a 15 lb counterweight.

Evaluation (for carrying capacity during the turning radius test):
The rover was unable to support the 100 lb load while attempting to conduct such a sharp turn. The added load exacerbated the bending in the steering supports and bogie connection so that when a sharp turn was attempted, the rover began to lean so severely that a team member had to catch it before it fell over. Therefore, the 100 lb load had to be removed and the rover then attempted the full turning radius test with the smaller load of just the battery and the counterweight. As has been stated previously, improvements to the stability of the rover by changing the material of the legs to thicker 80/20 members or a different material entirely is recommended before future testing with a 100 lb load.

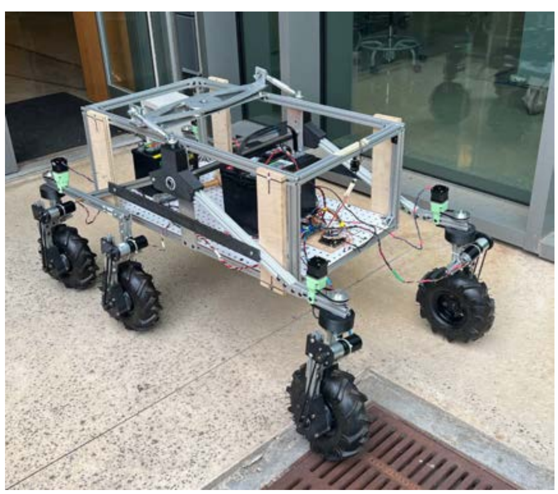

Figure 17: Loaded Rover with 50 lb battery and 15 lb counterweight

7. Obstacle Course

The team must design and build an obstacle course that contains obstacles that are at least the size of the radius of the wheels (5.1 inches) to test the mechanical systems of the Rover. The rover must be able to traverse obstacles resembling rocks (non-uniform spheres with a maximum diameter of 5.1 inches), and maneuver turns. These obstacles shall be used to demonstrate the effectiveness of the Rover's suspension and steering systems

The Obstacle Course Completion requirement was to ensure that the team constructed the necessary obstacle course for the final all-inclusive test of the rover. The following section details the components of the Obstacle Course Test that are relevant to the construction of materials. All other information can be found described in the previous sections.

Relevant Tests: Obstacle Course Test

Reference Section 4 under the Obstacle Course Test subsection for the **Objective and Test Scope.**

Test Plan (Specifically for construction of obstacles):

Instruments/Tools and Setup: There were three types of obstacles constructed for this requirement: a 5.1" obstacle, a 10.2" obstacle, and an obstacle that introduced uneven heights on one side of the rover. All three of the obstacles were constructed out of wood from the Makerspace. For the uneven terrain obstacle, wood screws and an electric drill were used to hold the pieces together.

Procedure: As demonstrated in Figure 17, the three obstacles were placed in a line to create the course for the rover. The rover was required to go through the course once while putting the left-side wheels on the obstacles, conduct a 12" turn at the turning point, and then repeat the course with the right-side wheels.

Acceptance Criteria:

In terms of this construction requirement, the acceptance criteria was solely based on if all types of obstacles were made and placed in a course for the rover to run.

Test Results:

Since all three obstacles were constructed to the appropriate 5.1", 10.2". and uneven requirements and placed in a course, as shown in Figure 17, this requirement was fulfilled.

For results on how the rover completed the obstacle course, reference Section 4 under the Obstacle Course Test subsection.

Evaluation:

For an evaluation on how the rover completed the obstacle course, Reference Section 4 under the Obstacle Course Test subsection.

IV. Conclusions

Over the course of one academic year, the team attempted to augment the locomotion of the planetary rover through mechanical improvements to the suspension and steering systems. The final goal given by our sponsor was for the rover to complete an obstacle course that contained obstacles the height of the radius of its wheel (5.1”), uneven terrain, and turns with a 12-inch turn radius. To achieve this goal, the team was successful in constructing new suspension and steering systems on a rover prototype that previously had none. While the final rover prototype implemented a rocker bogie suspension and independent steering system, the overall prototype was unsuccessful in achieving the goal of completing the obstacle course. However, while the overall goal was not achieved, each independent subsystem demonstrated promise and success.

Of the seven project objectives decided upon by the team and Project Sponsor, three were achieved, three were partially achieved, and one was not achieved. The three requirements that were achieved through successes in a subset of our nine prototype tests include the Clearance, Dimensions, and Obstacle Construction requirements. These three requirements were related to being able to conduct the other six tests: making sure the rover would not collide with obstacles, ensuring the rover could move around the CSI where testing took place, and ensuring the team constructed the necessary components for the obstacle course test. The one requirement that was a complete failure was the Carrying Capacity requirement since the rover was not able to support a 100 lb load on top of its battery load without collapsing. The maximum load not including the 50 lb battery was about 15 lbs. This means the rover held over 100 lbs in total when including the battery weight.

The three partially achieved requirements were the Suspension, Steering, and Ability to Overcome Obstacle requirements. The team concluded that the Suspension requirement was partially achieved because the implemented rocker bogie suspension was an upgrade from the original design with immobile joints and it was able to interface with the steering system. The rover was able to conduct wide turns with the steering system while supported on the suspension system. Furthermore, the team concludes this requirement a partial success because the rocker bogie fundamentally functioned as expected, with the rocker and bogie joints rotating separately, and the two sides of the rover moving independently using a differential bar. All components of the rocker bogie were implemented. However, this requirement was a partial failure due to the inability of the rover to maneuver over obstacles larger than 0.5”. This failure was caused more by the material used for the suspension rather than the suspension design itself. Similarly, the Ability to Overcome obstacles requirement failed in the sense that the rover could not drive up and over an obstacle of 5.1”, but was a success when the rover was placed on the obstacles and did not exceed our decided pitch and roll angle limits or tip over. The team concluded that the Steering requirement was partially achieved because the team was able to implement an active steering system that was controlled through a joystick. The rover could conduct a slow and wide turn to either side by individually turning the two front and two rear wheels. However, this requirement was also a partial failure because the minimum turning radius of 12 inches was not achieved. Due to stability issues, the turning radius of the rover was unmeasurable.

The rover is currently a working prototype, with the ability to move forward and backward and turn left or right very slowly. However, the prototype still contains problems with the stability. The team has concluded that the failures of this prototype originate from several sources that are contributing to a lean of the rover, introducing a large instability whenever the rover moves. The first source of instability is the torsional bending of the 80/20 members as seen in Figure 13. While the rocker and bogie components of the suspension interfaced together correctly, and independent steering was implemented on four of the six wheels, this bending prevented either subsystem from being a complete success. A second source of instability was the bending of the gearboxes. All six wheels were able to bow inward and wobble as the rover moved forward, adding to the overall side to side lean of the rover. The slipping of the drive belts on the pulleys mounted on the gearboxes contributed to the rover's inability to go over obstacles because the pulley grooves were not deep enough to keep the timing belt engaged when resistance was met by the wheel hitting the obstacle. The final source of instability was the steering column shafts, which were too small and contained no grooves for the set screws. These two factors combined meant that once an obstacle was hit, the wheels would get pulled under the chassis of the rover from bending in the shaft, or the holding torque from the steering motors would fail completely because the shaft slipped from the set screws.

The team primarily recommends design changes that will increase the overall stability of the rover. These include using thicker 80/20 members or a stronger metal entirely for the leg members of the suspension system. For the suspension, the team also recommends using the same main join (Fig. E3) be made out of metal instead of nylon to reduce flexing. Improvements to the gearboxes are needed to reduce the wobble in the wheels and prevent the sway of the rover, and using metal pulleys mounted to the gearboxes would make for a stronger grip by the driving belt. Finally, the team recommends using a shaft with a diameter of 0.5 inches or more to ensure the steering column does not get pulled under the rover.

While the rover prototype completed by the team was not able to achieve the final goal, individual components of the design were deemed successful. The team not only proved that a rocker bogie suspension could interface with an independent steering system, we demonstrated the implementation of the rocker bogie suspension with a differential bar that kept the chassis level when tested statically. The final prototype is thus a preliminary proof of concept for the rocker bogie suspension and independent steering system and requires only improvements to overall stability to eventually achieve the sponsor's goal.

V. Appendices

Appendix A: Setup, Operating, and Safety Instructions

Setup Instructions:

The rover's microcontroller is loaded with its C++ test control program as shown in Figure G3. The microcontroller will boot with this program when +12V is applied to the power distribution circuit. New programs can be flashed using the microcontroller's onboard UART connection. It is recommended to connect to the microcontroller over USB and upload new programs compiled for the ESP32 module onboard. It is recommended not to upload programs to the ESP32 while the rover's motors are powered, because some of the pins which get configured as GPIO when the microcontroller boots are also involved in the onboard flash controller's operation and the UART communication process. The current program and wiring configuration avoids using these pins, but further expansion of the system may involve them, so it is best practice to start up the microcontroller *before* powering on the rover by supplying it with +5V over USB or the +5V bus with a Dupont wire.

Operating Instructions:

The rover's test program is controlled using an analog joystick that is connected to the microcontroller's analog input pins. Moving the joystick up or down drives the rover forward or backward, and moving it left or right causes the stepper motors to turn the four steering wheels to prepare the rover for a turn. The front and back sets of wheels turn opposite of each other for an effective turn radius. Connecting the microcontroller to a computer over USB allows the user to read serial messages from the rover at 115200 baud rate. The program is currently configured to simply output the direction the rover is moving in, and the analog reading of the joystick in that direction - however, the program can easily be configured to relay more complicated diagnostic information and even sensor feedback this way.

Safety Instructions:

It is important not to operate the rover past its mechanical and electrical limits. Ensure that during operation, the legs of the rover do not begin to twist excessively, and that the steering columns are clear of the sides of the rover chassis so that none of the 80/20 hardware catches on the frame. The same applies to the wiring; slack has been introduced to each of the twisted wire bundles going to each of the ten motors, but if the operator is not careful, excessive steering can twist these wires out of their screw terminals and damage the stepper motors or their drivers. Be careful to follow the wiring guide in Figure G5 carefully, and adhere to Table G1 when modifying the rover's firmware to ensure that the microcontroller is configured correctly and the rover will not behave unexpectedly. Each of the stepper drivers is rated for the amount of current being drawn, even when stalled, but the heatsinks on them still get very hot during usage. It is advised to pay attention to the condition of these drivers, and not touch the heatsinks during or directly after operation. The same goes for the LM7805 voltage regulator, which is responsible for delivering power to the logic ICs of the stepper drivers and to the microcontroller. The condition of the wiring should be routinely inspected to ensure that there are no loose connections or burnt components.

Appendix B: Applicable Codes and Standards

This project used the IEEE Code of Ethics to inform team activities, communication, and design decisions. Our team strove to work in line with the standards of professionalism set forth by the three sections of the IEEE Code. Portions 5, 6, and 7 of the IEEE code are particularly relevant. In accordance with section I.5, our team followed the "seek, accept, and offer honest criticism of technical work" as well as "credit properly the contributions of others" statements. Furthermore, in compliance with section I.6. our team strove "to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience" by seeking out expert training and guidance when faced with a task we lacked the technical training to complete. Our team also treated all persons fairly and with respect, as outlined in section II.7. of the IEEE code of ethics. We also worked to reflect this code in our design work, ensuring to respect standards of personal and community safety while creating a well-documented project prototype.

Below are some preliminary selections of specific engineering standards that were relevant to the planned scope of our project.

- **SAE J3206 (2021): Taxonomy and Definition of Safety Principles for Automated Driving System (ADS)**
  This standard covers general safety principles for automated driving systems. As our rover will be able to drive autonomously via loaded programs, these standards are relevant to how we design these programs and implement them in practice.

  "This SAE Information Report provides guidance for the consideration and application of the safety principles for the development and deployment of ADS and ADS-equipped vehicles."

- **SAE J2950 (2020): Maintenance of Batteries and Battery Charging and Servicing Facilities**
  This standard deals with proper methods for hands-on servicing and upkeep of lead-acid batteries like those used in our rover design, and will help inform our testing and management of these batteries.

  "This SAE Aerospace Information Report (AIR) covers, and is restricted to, hands-on servicing/ maintenance of industrial lead acid batteries used solely for motive power and exclusively for ground support equipment (GSE)."

- **NEMA ICS 16 (2001): Motion/Position Control Motors, Controls and Feedback Devices**
  This standard applies to the four steering stepper motors used in our rover, detailing power requirements and methods of feedback control for such motors. The motors used in our rover are classified as NEMA 17.

  "Covers rotational electric servo and stepper motors and their power requirements, feedback devices and controls intended for use in a motion/position control system that provides precise positioning, speed control, torque control or any combination thereof."

Appendix C: Additional Testing Results

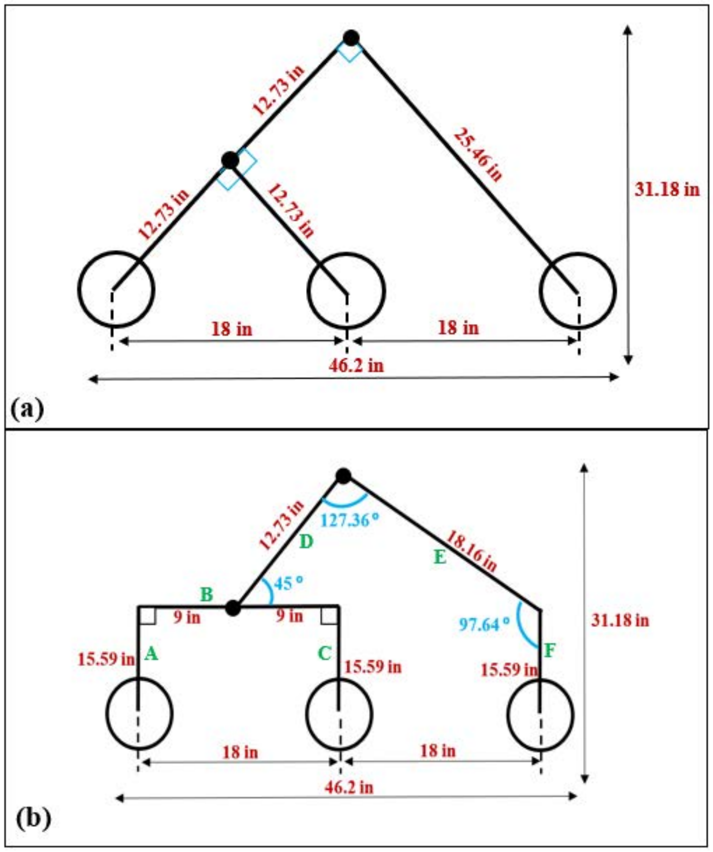

Figure C1: Calculated angles and lengths for two different styles of rocker-bogie suspensions using the known total length of the rover. (**Left**) Typical angled rocker-bogie with 90-degree angles and only four linkages. (**Right**) The team's design for a rocker bogie with vertical steering columns, and the resulting necessary lengths and angles.

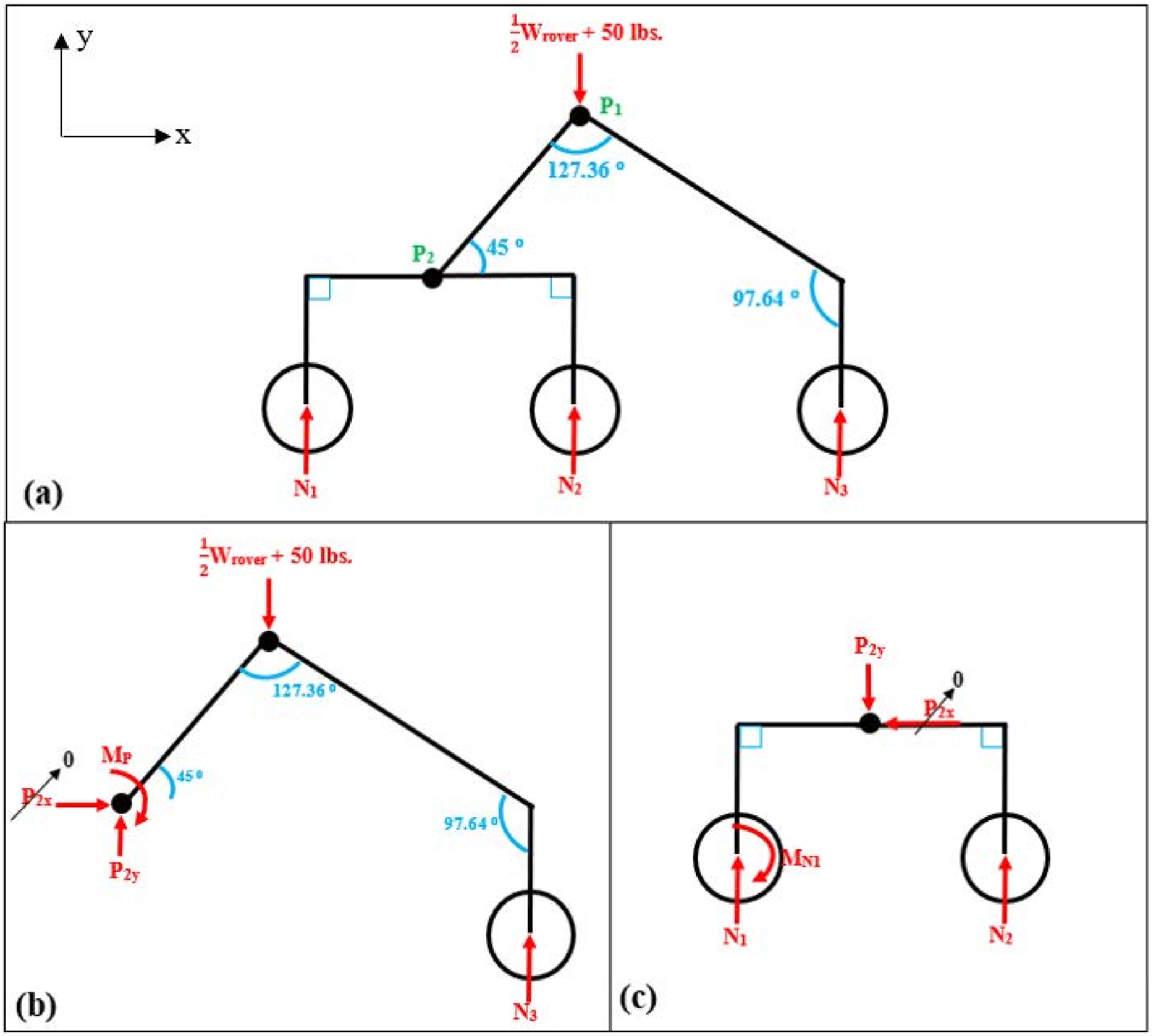

Figure C2: (a) Force diagram for the whole suspension system with half the total weight of the rover and the additional 100-lbs and the three normal forces. (**b**) Individual rocker body with the pin force at P2. (**c**) Individual bogie body with the same pin force at P2

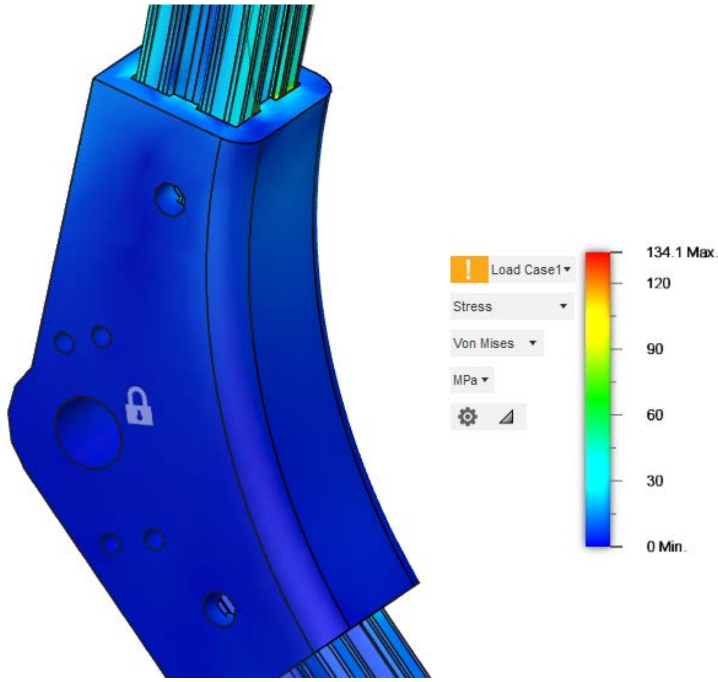

Figure C3. ABS Plastic Rocker-Bogie Joint Stress Test. The lighter blue at the connection between the aluminum beam and the joint signifies greater stresses and more potential for failure.

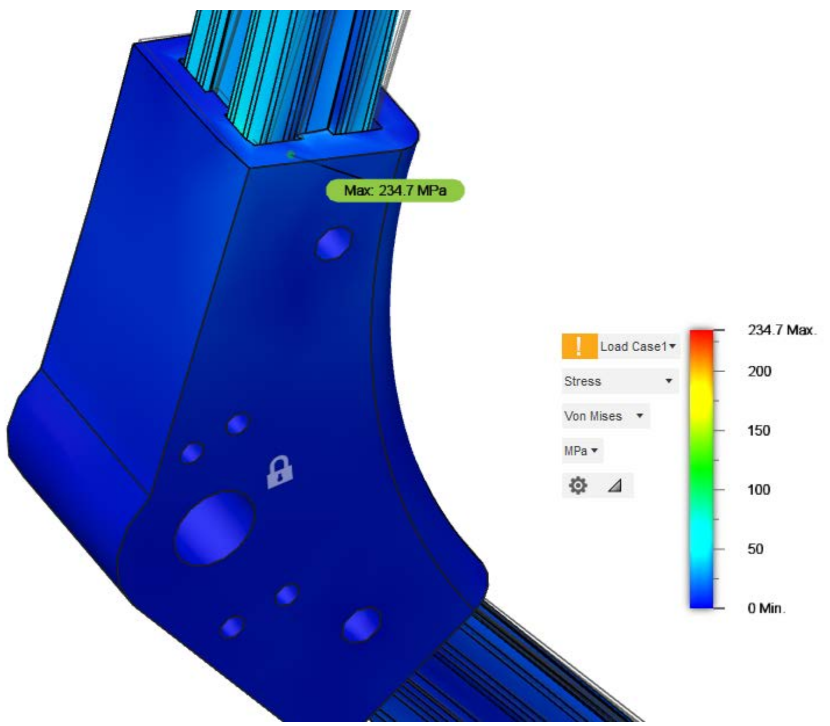

Figure C4. Aluminum Rocker-Bogie Joint Stress Test

Appendix D: Complete Bill of Materials

Part Description (Qty)	Manufacturer	Vendor	Total Cost
1/4 x 8" Alum Plate 6061-T6 (1)	Westbrook Metals	Westbrook Metals	38.00
1/4-20 T-Nuts 25 Pack (2)	Taylor Toolworks	Amazon	25.98
12V Deep-Cycle Marine Battery (1)	EverStart	Walmart	102.42
27:1 Geared Stepper Motor (1)	StepperOnline	Amazon	40.15
3M .5 pitch 18mm Screws (1)	McMaster-Carr	McMaster-Carr	23.43
5:1 Geared Stepper Motor (1)	Stepper Online	Amazon	159.56
5x A4988 Stepper Motor Driver (1)	Kiro & Seeu	eBay	8.99
8 ft 80/20 Length (1)	80/20	Grainger	50.00
Bolt Combo 1/4-20 button head socket (1)	MewuDecor	Amazon	17.01
DC Motor (Driving) (4)	ABB	Robotshop	360.00
Flange Bearings 8mm (8)	Sydien	Amazon	22.34
200xL025 Timing Belts (2)	McMaster-Carr	McMaster-Carr	24.81
M3x0.5 mm thread socket screw x50 (1)	McMaster-Carr	McMaster-Carr	10.00
⅜”x1” Sleeve Bearings (4)	McMaster-Carr	McMaster-Carr	26.07
1”x1.5” Sleeve Bearings (2)	McMaster-Carr	McMaster-Carr	44.91
Timing Pulley 20 & 80 2 sets	DORUNDEA	Amazon	33.98

Appendix E: Fusion 360 Designs

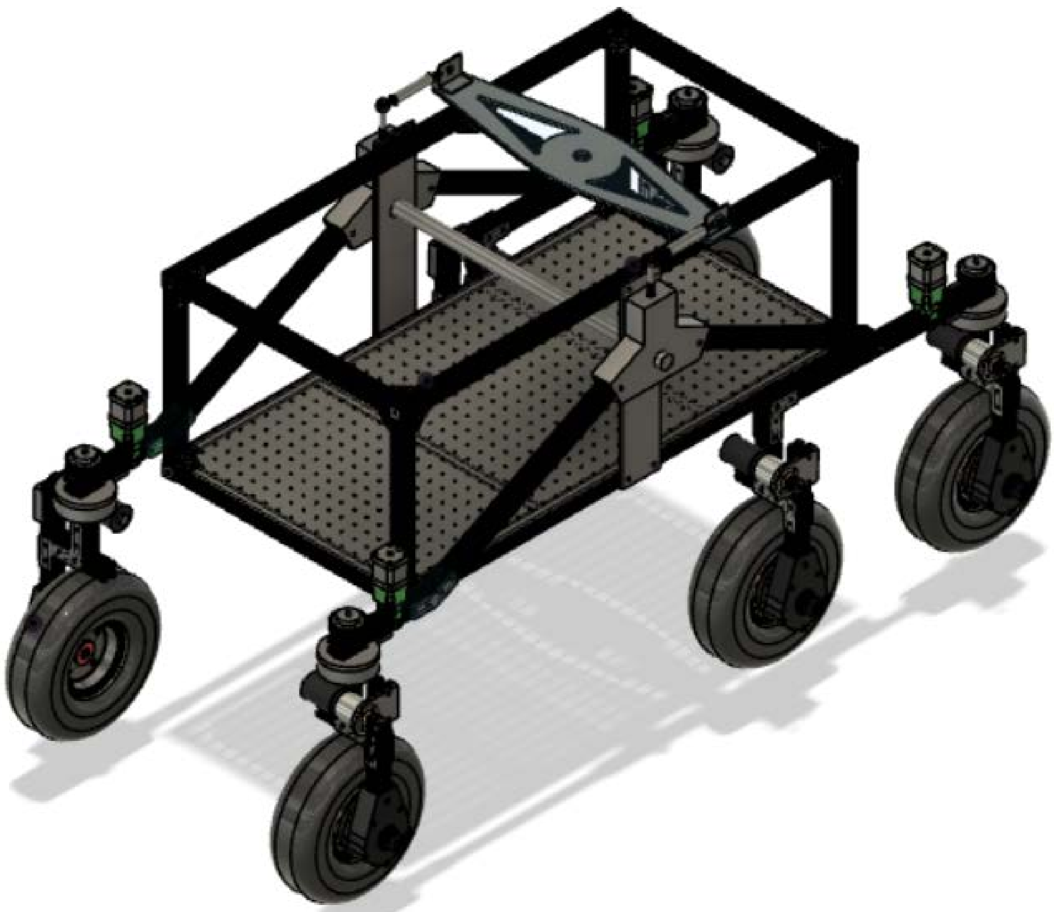

Figure E1: Total Fusion 360 Mockup of the Final Rover Assembly

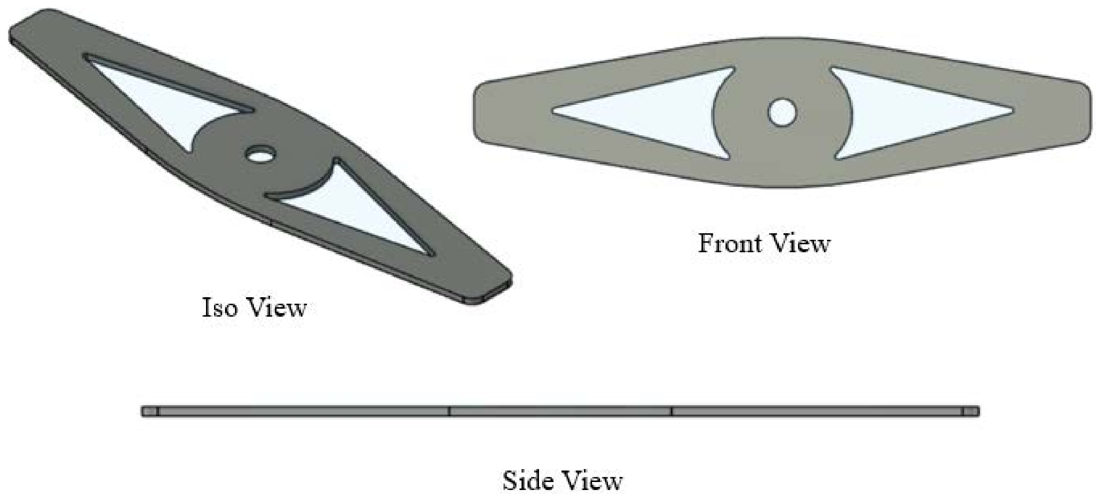

Figure E2: Fusion 360 Differential Bar Design and Drawing

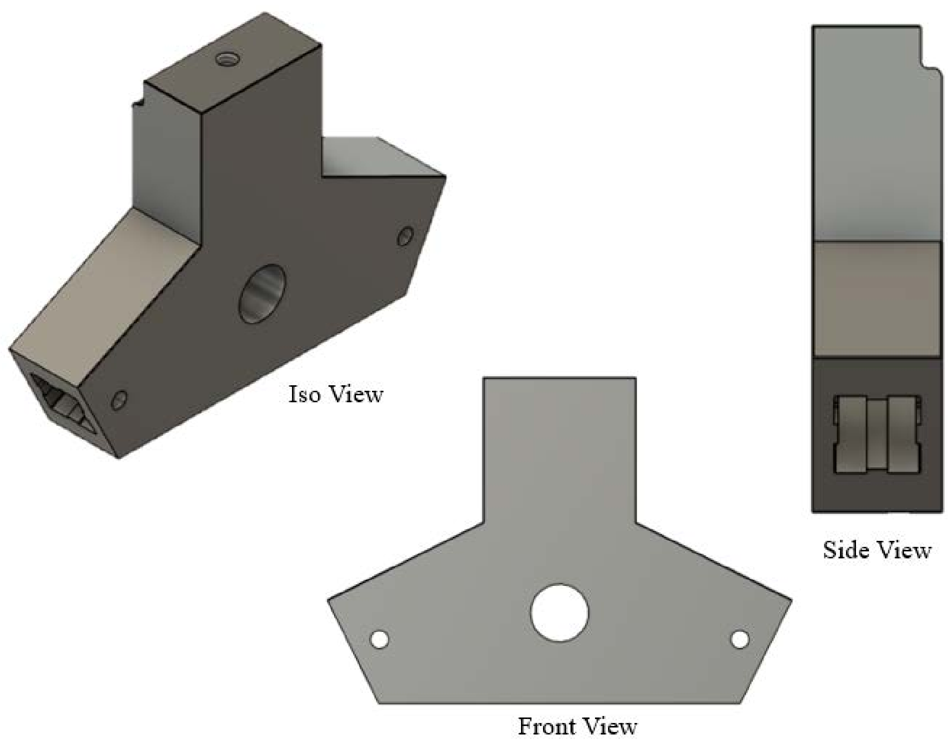

Figure E3: Fusion 360 Main Rocker-Bogie Joint Design and Drawing

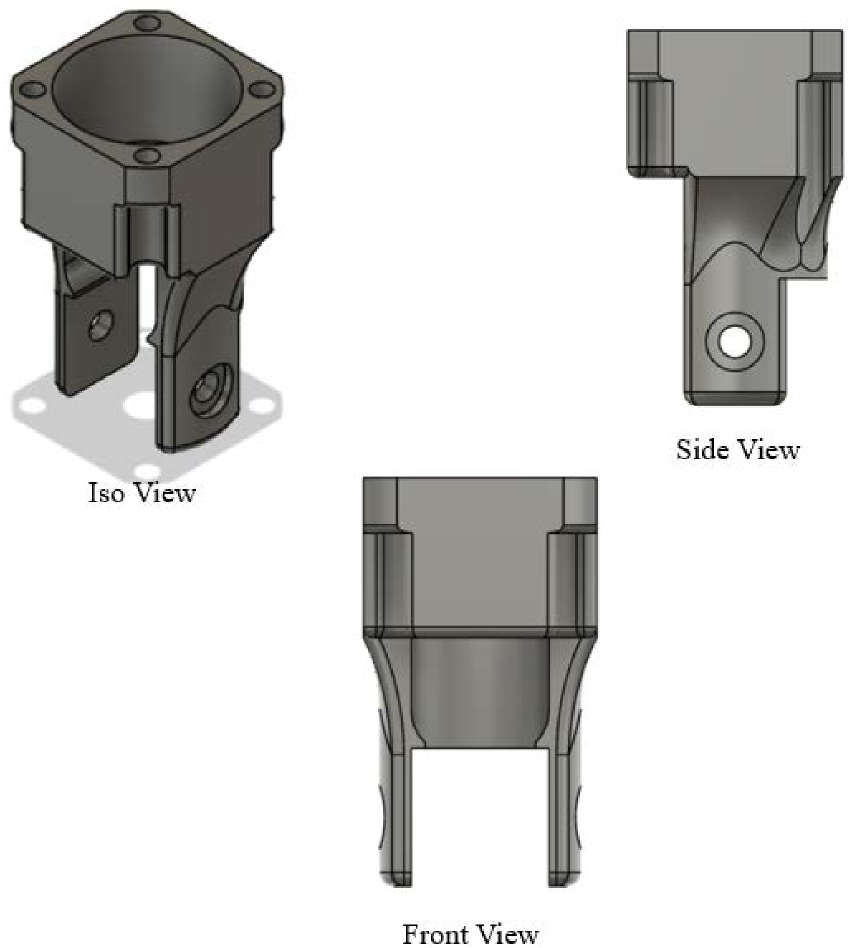

Figure E4: Fusion 360 Custom Designed and 3D printed Steering Motor Mount

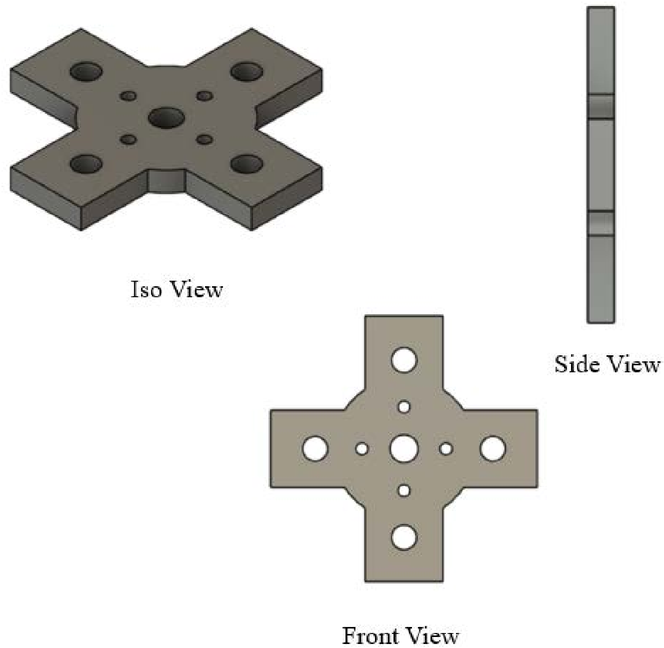

Figure E5: Custom Steering Column Connection Piece

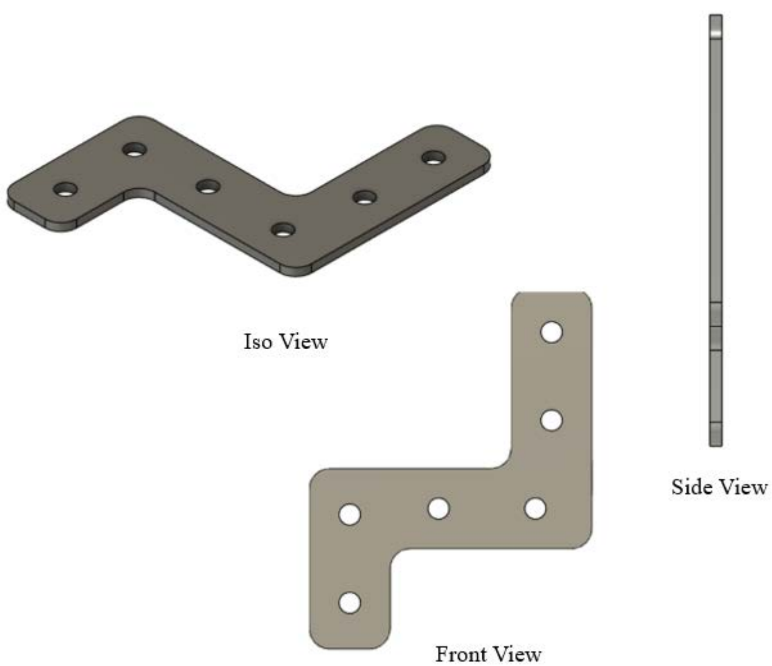

Figure E6: Fusion 360 Custom Steering Column Faceplate

Figure E7: Mounted Steering Column Faceplate

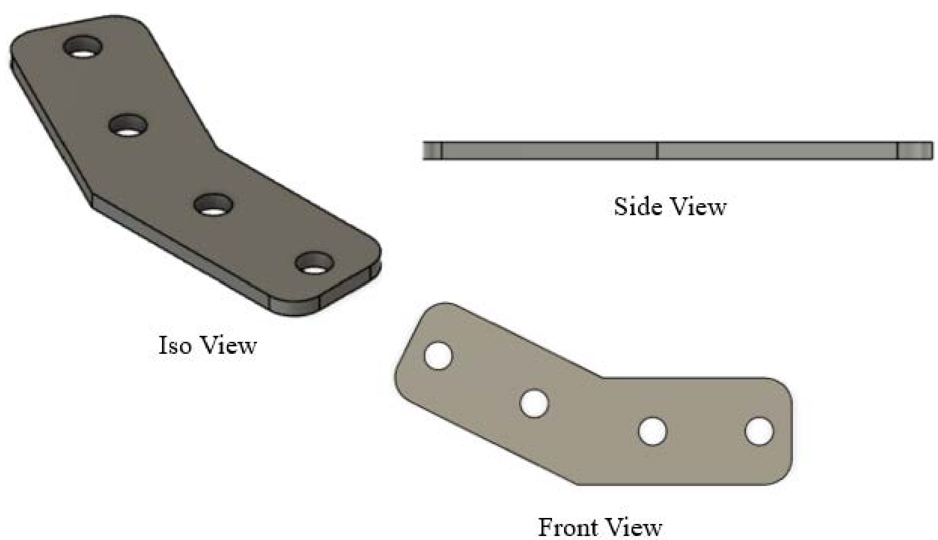

Figure E8: Custom Steering Column Joint

Figure E9: Steering column assembly before (left) and after (right) mounting to the main rover body with the 3D printed supports

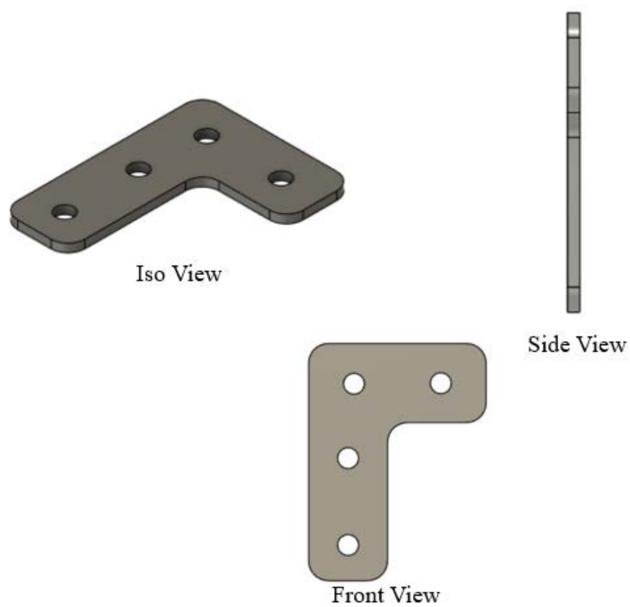

Figure E10: Fusion 360 90-Degree Suspension Connection Joint

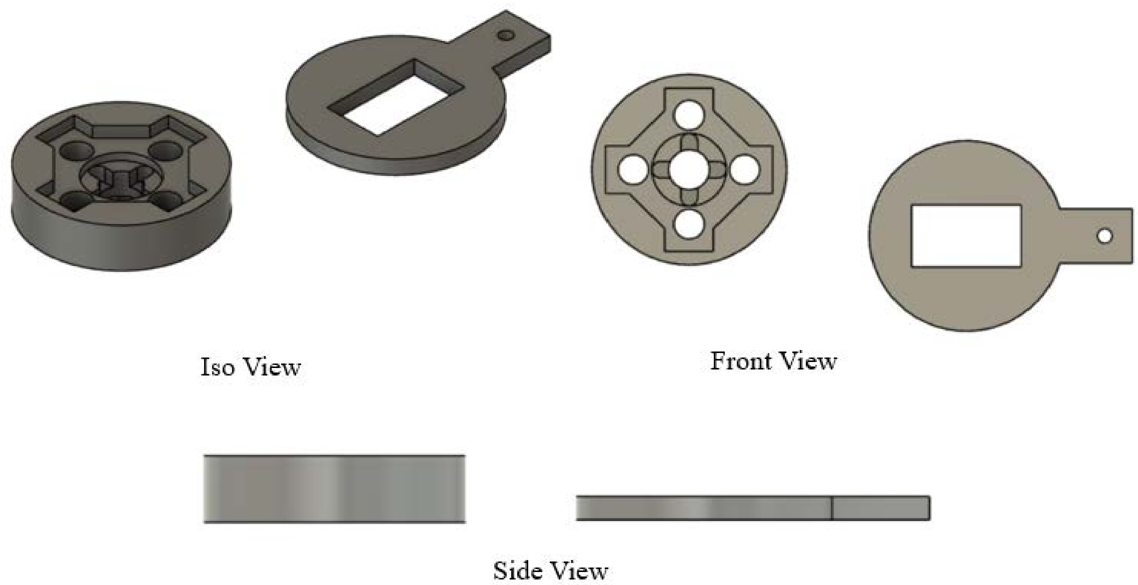

Figure E11: Fusion 360 Custom 3D Printed Steering Supports

Appendix G: Electronics

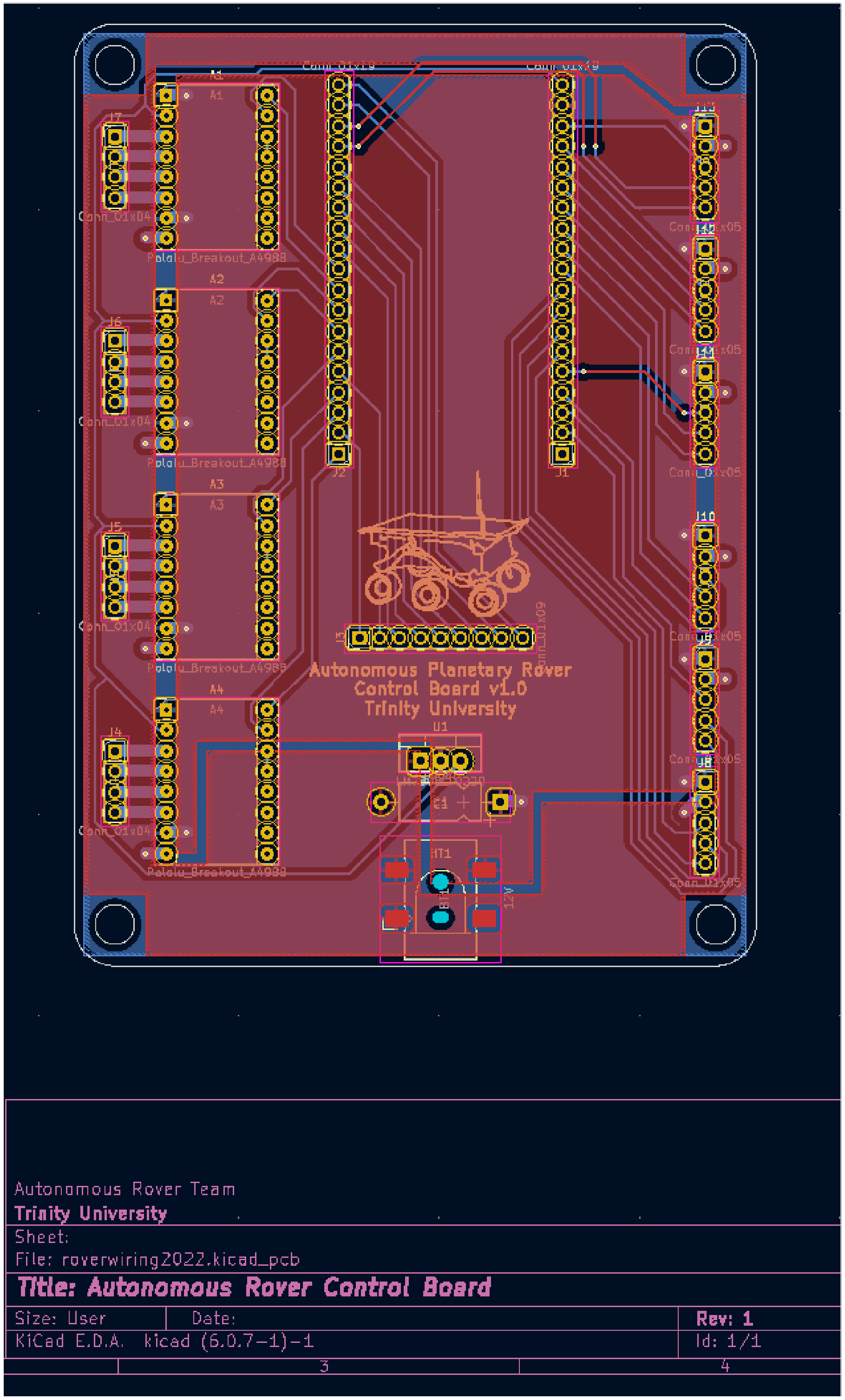

Figure G1. KiCAD PCB Schematic of Initial Two-Layer ESP32 Control Board Prototype

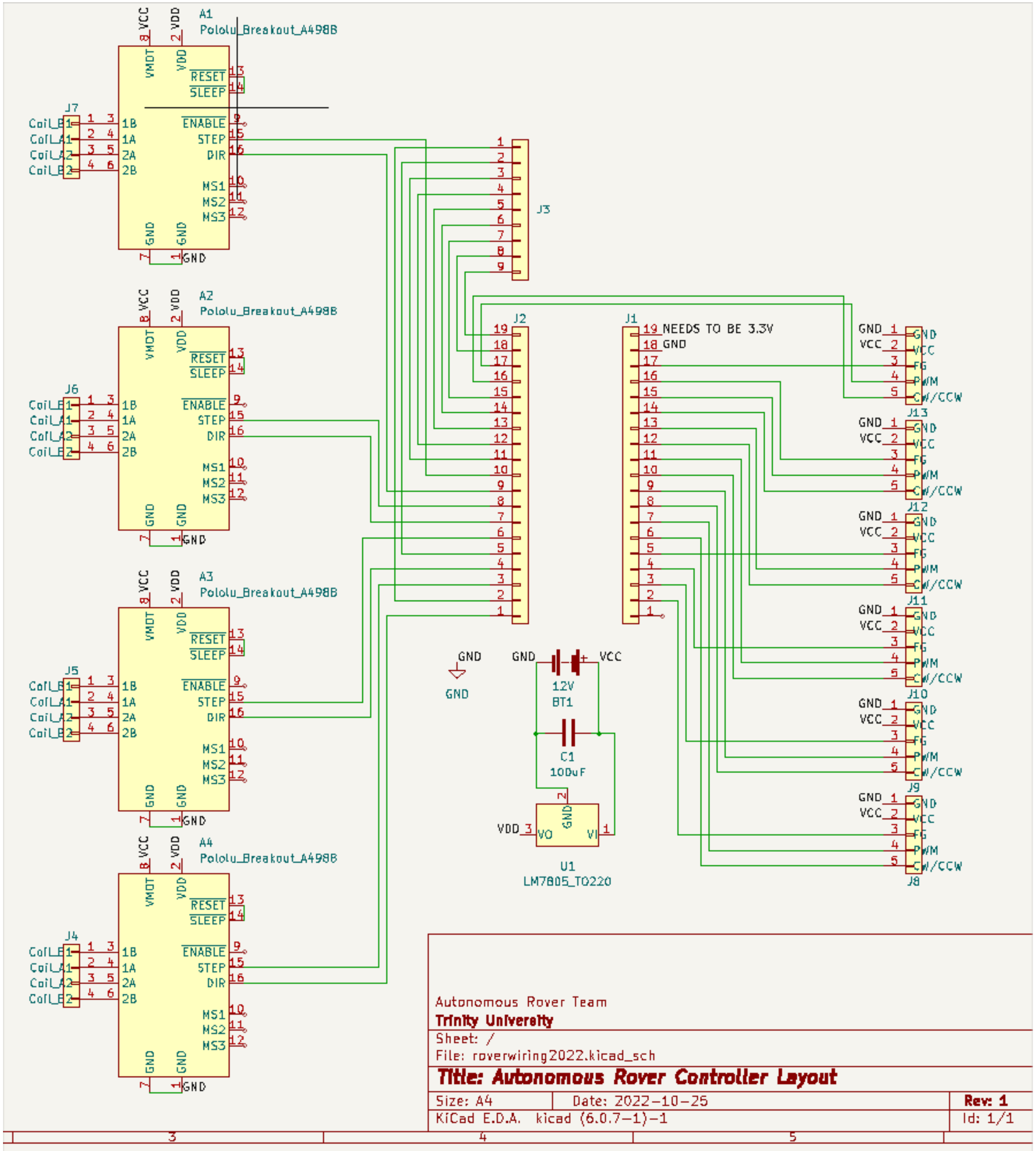

Figure G2. Initial KiCAD Wiring Diagram for Rover Control and Power Distribution

```
void drive(int dir, int pwm){     // Drive Function
  digitalWrite(dirLMotor, dir);
  digitalWrite(dirRMotor, !dir);
  digitalWrite(pwmLMotor, LOW);
  digitalWrite(pwmRMotor, LOW);
  if(!messageFlag){
    Serial.println("DRIVING");
    messageFlag = 1;
  }
  Serial.println(analogRead(motorInput));
}

void read(){
> while(analogRead(stepperInput)>2500){    // LEFT ···
> while(analogRead(stepperInput)<1500){    // RIGHT ···
> while(analogRead(motorInput)<1700){    // FORWARD ···
  while(analogRead(motorInput)>2000){    // BACKWARD
    drive(CCW, 0);
  }
  digitalWrite(pwmLMotor, HIGH);          // STOPPED
  digitalWrite(pwmRMotor, HIGH);          // STOPPED
  if(messageFlag){
    Serial.println("STOPPED");
    messageFlag = 0;
  }
}

> void setup() {···

void loop() {
  read();
  delay(50);
}
```

Figure G3. Collapsed overview of a basic test code segment that responds to analog joystick inputs

Pin Number	ESP32 GPIO Pin*	Type	Position	Description
1	22	PWM OUT	Right	Brushless motor speed control wire
2	23	Digital OUT	Right	Brushless motor direction control wire
3				Currently unused
4				Currently unused
5				Currently unused
6				Currently unused
7	12	PWM OUT	Front Right	Stepper motor driver speed pin
8	13	Digital OUT	Front Right	Stepper motor driver direction pin
9	32	PWM OUT	Back Right	Stepper motor driver speed pin
10	33	Digital OUT	Back Right	Stepper motor driver direction pin
11	25	PWM OUT	Front Left	Stepper motor driver speed pin
12	26	Digital OUT	Front Left	Stepper motor driver direction pin
13	27	PWM OUT	Back Left	Stepper motor driver speed pin
14	14	Digital OUT	Back Left	Stepper motor driver direction pin
15				Currently unused
16				Currently unused
17	GND	Power		Ground
18	5V	Power		5V line from LM7805 regulator
19	19	PWM OUT	Left	Brushless motor speed control wire
20	21	Digital OUT	Left	Brushless motor direction control wire
				***REFERENCE LATEST ROVERCONTROL CODE**

Table G4. Pin mapping of electrical subsystem

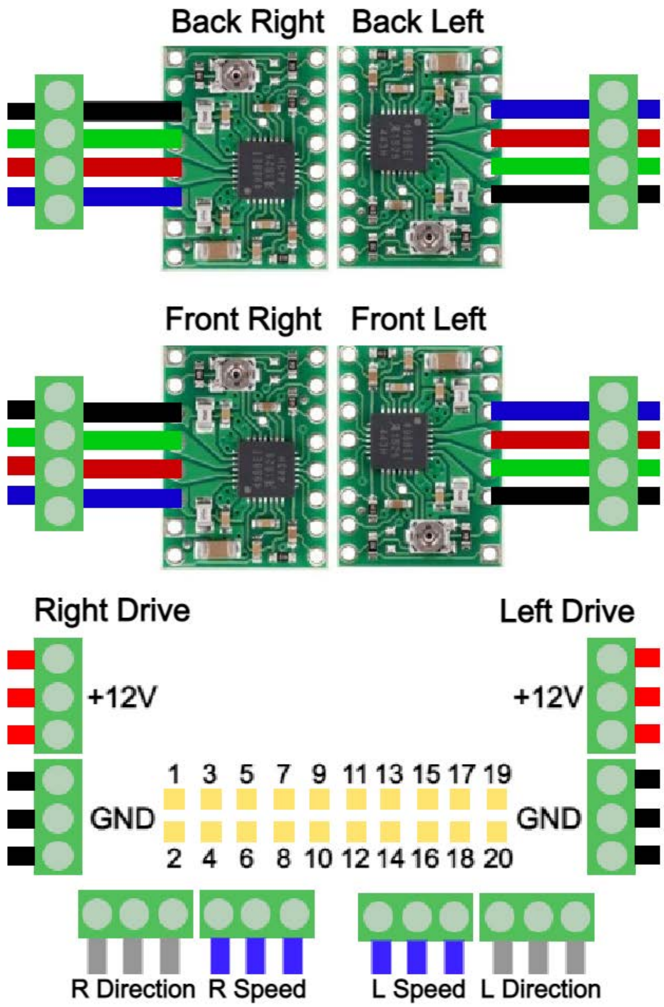

Figure G5. Color-coded wiring diagram for stepper and drive motors

Bibliography

SAE. (2021). *Taxonomy and Definition of Safety Principles for Automated Driving System (ADS)*. SAE J3206.

SAE. (2020). *Recommended Practices for Shipping Transport and Handling of Automotive-Type Battery System - Lithium Ion*. SAE J2950.

NEMA. (2001). *Motion/Position Control Motors, Controls and Feedback Devices*. NEMA ICS-16.

The Institute of Electrical and Electronics Engineers. (1990). *IEEE Code of Ethics*.