Faculty of Engineering

Detailed Design of a Search and Rescue Robot

MTE 380

Prepared by

Group 3

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3B Mechatronics Engineering

February 29, 2016

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Prof. Bill Owen
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Dear Prof. Owen,

This report, entitled “Detailed Design of a Search and Rescue Robot” was prepared as Group 3’s detailed design report for the MTE 380 search and rescue project. The purpose of this report is to describe the specific designs decisions made to accomplish our initially proposed design.

We would like to acknowledge your assistance in defining and clarifying the objectives of the project, and clearing up confusion regarding the reporting structure and content.

We are the sole authors of this report and, unless otherwise stated and properly referenced in the report, the entire content of this report is original work done by us. We have all read the report and are aware of the content. The content of this report has not received credit in this or any other course that we have taken in the past or are currently taking at this time.

Sincerely Yours,
Group 3

Blair Chau	Ryan Chung	Jasdeep Dhillon
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Executive Summary

Humans are now able to immigrate from Earth to Mars due to large technological advancements. However, due to a collision on Mars from one of these trips, human beings sent from Earth to Mars as settlers are stranded and in need of food and water supplies in order to survive. Because of the danger posed, a rescue mission can only be conducted by way of an autonomous vehicle. The vehicle must be able to go over a mountain range and deliver supplies to the base the stranded humans have temporarily set up.

The initial, agreed upon objectives, constraints, and design selection criteria are reiterated from the conceptual design phase. The design selection criteria against which the design alternatives are compared against are weight, cost, travel time, construction time and number of human interventions possibly required. An initial budget of $215 was set for the project, although after actual component procurement, total costs have gone $93 over budget.

A work breakdown structure is presented in this report with timelines for important deadlines and milestones. As per the planned schedule, a detailed design has been finalized including all electronics and software design.

The previously selected general design involves traveling up a ramp on the edge of the mountain range. Detailed mechanical design includes selection of a purchased enclosure and paired 60 mm and 80 mm diameter wheels for ramp guidance. Detailed electrical design includes selection of a stepper motor, an Arduino motor shield for control, ultrasonic sensors for distance measurement, an inertial measurement unit for ramp detection and a 12 V battery for power supply. Detailed control system design includes selection of a boundary offset algorithm for distance detection, a tilt detection algorithm for ramp guidance, and a reference distance data algorithm to detect the base to be found.

Testing involving the individual components should be performed as a next step, followed by unified functionality testing as well as detailed sensor testing to obtain relevant metrics including hold time, range and resolution.

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1 Introduction and Background

This section provides an introduction to the design problem of interest, and outlines in more detail the solution requirements by exploring the nature of this problem.

1.1 General Background

It is the year 2048. Advancements in technology have propelled humanity's progress as a society faster and further than it has ever been. Earth has finally united as a planet and humanity's brightest have gathered under a single banner to tackle the issue of a millennium; terraforming and inhabiting Mars. An organization called Humanity's Unified Bodily Relocation Initiative in Space (HUBRIS) has been formed and its headquarters has been built on Mars right at the base of the largest known mountain in the Solar System, Olympus Mons. With future expansion, traveling, and tourism in mind, HUBRIS has constructed basic infrastructure in the form of a road traversing the mountain and a monumental steel wall encasing the mountain. To help build up the population, immigrants from Earth are periodically flown in on ships controlled from Earth. In one of these trips, the ship encountered unexpected turbulence which could not be avoided due to control latencies caused by the long distance between Earth and Mars, resulting in an emergency landing on the other side of Olympus Mons. The harsh climate on Mars renders it impossible for HUBRIS to develop a method to retrieve them before they die of starvation. Instead, they devised a plan to create a smaller scale project to deliver supplies to the immigrants in order to buy time to rescue them. As a result, project Destination Oriented Wireless Navigation Fixed Autonomous Logical Locator (DOWNFALL) was born.

1.2 Needs Assessment

As it stands with their given food and water supply, the immigrants will not survive for more than three months. In order to keep them alive, a method of traversing the mountain and delivering these supplies to the temporary base must be devised before then.

1.3 Problem Formulation

The overall problem that must be addressed with a designed engineering solution is described in this section. The problem is broken down and analyzed in terms of the functional goals of a successful solution. These are then outlined as specific objectives and constraints for the design. The design selection criteria are then derived from the design objectives.

1.3.1 Problem Definition

The general problem to be addressed is the following: a device must be designed and constructed to be able to travel to the opposite side of a mountain range in order to conduct a search and rescue mission.

1.3.2 Desired Functions and Goals

The functions necessary for a design to successfully address the design problem are listed below:

- The designed device should be able to travel from a starting location on one side of the mountain range to a destination located on the opposite side.
- The device should be able to detect and climb on top of the base at the destination to deliver supplies.

Listed below are goals which pertain to equipment availability and physical limitations:

- The device should remain within specified boundaries of the mountain range area at all times while it is operating.
- The device should initially be under a specified size that allows for manual transportation.
- The device should be controlled by a single specified microcontroller.

Additionally, there are goals correlated to the performance and optimization of a design, which are listed below:

- The time required for the device to travel from its starting location to the destination should be as low as possible.
- The device should have minimal mass.
- The device should accomplish its required tasks autonomously.
- The time required to design and construct the device should be as low as possible.
- The device should have minimal cost.

1.3.3 Design Constraints

The design constraints are derived from the concrete project requirements and the functions and goals that are absolutely necessary to solving the design problem. At a bare minimum, the design must carry out the search and rescue task, use the available microcontroller and have a sufficiently small starting size. These constraints are quantified below:

- The device must be able to locate and travel to a destination of variable location on the opposite side of the 0.9 m high mountain range.
- The device must be controlled solely by an ATMega2560 microcontroller.
- The device must remain within the 2.4 m by 4.8 m site while performing its required tasks.
- The dimensions of the device must be within 0.6 m by 0.6 m by 0.6 m prior to being activated.

1.3.4 Design Objectives

The design objectives are selected by expanding the goals for the design which will influence the performance or engineering costs. The performance index depends upon both the device mass and the search and rescue time. Search and rescue time is in turn influenced by the number of times a human intervention/troubleshooting becomes necessary. Engineering costs are broken down into financial costs and required engineering effort for design and construction. These objectives are quantified below:

- The device should travel from Base 1 to Base 2 in under 60 s.
- The device should have a mass under 5 kg.
- The device should require 0 instances of human intervention during operation.
- Total design/construction time for the device should be under 500 h.
- The total cost for designing and constructing the device should be less than $215 (CAD).

1.3.5 Design Selection Criteria

The design selection criteria used to compare several viable design alternatives are derived from the design objectives listed above. These criteria are shown below:

- Mass(kg)
- Cost (CAD)
- Travel time (s)
- Construction time (h)
- Human Intervention Instances (#)

1.3.6 Key Design Problems

The search and rescue tasks can be broken down into the following smaller design problems:

- The device requires a method of transportation/movement that can be controlled or predetermined.
- The device requires a method of travelling across the mountain range.
- The device requires a method of determining the location of the destination base.
- The device requires a method of determining its own location relative to the base, the area boundaries, the mountain range and the ramp over the range.

The second design problem is specifically focused on travelling over the mountain range, as travelling around the range is not permissible. The options of tunneling under or through the range are rejected due to the safety concerns that would be raised by the methods of doing so, along with the unreasonably high costs of acquiring the necessary equipment.

Taken together, these smaller tasks are the essential, minimum requirements that any viable design must be able to accomplish. The specifics of using location to adjust or control the movement of the device are discussed in the detailed design sections of this report.

2 Project Management

The following section outlines the project management details of the project. This section provides information regarding the members of the team, the work breakdown, task distribution, risk mitigation, and the budget. This information paves the path and direction the team will follow for the rest of the project.

2.1 Schedule

The project schedule is displayed below in Figure 1 as a Gantt chart. Within the Gantt chart, the milestones are highlighted in green with the subtasks in white. As the subtasks are completed, the completion of the milestone approaches more towards 100 percent. This is represented by the progress bar which provide a visual indication of the project completion. For milestones, the expected duration of work for the milestone is shown in light blue. As progress is made towards the completion of the milestone, the light blue bar is filled by the darker blue bar. For subtasks, the indications are similar with the use of light green and dark green instead. Figure 1 below shows the Gantt Chart for this project which indicate the start and end date of the task as well as the owner of the specific task.

Project DOWNFALL	**Start Date**	January 8, 2016					
HUBRIS	**Total Duration**	63					
Task	**Start Date**	**End Date**	**Duration (Days)**	**Percent Complete**	**Owners(s)**	**Detailed Description**
1.0 Milestone 1	2016-01-08	2016-01-22	15	100.00%		
1.1 Proposal	2016-01-08	2016-01-22	15	100.00%	Ryan	Construction Check #1
2.0 Milestone 2	2016-01-25	2016-02-05	12	100.00%		
2.1 Sensor Selection	2016-01-25	2016-01-27	3	100.00%	Tian, Anthony	Kinematics, torque, stress, etc calcuations.
2.2 Mechanical Calculations	2016-01-25	2016-01-27	3	100.00%	Jeremiah, Blair	Includes motors, sensors, power
2.3 Part Selection	2016-01-25	2016-01-27	3	100.00%	Anthony, Tian	Design done in CAD.
2.4 Chassis Design	2016-01-28	2016-01-29	2	100.00%	Jeremiah, Blair	Group meeting.
2.5 Mechanical Design Review Meeting	2016-01-29	2016-01-29	1	100.00%	Ryan, Jeremiah	Purchase motors, sensors, and other major
2.6 Purchase Components	2016-01-29	2016-02-01	4	100.00%	Anthony	Two buisness days out of four total days.
2.7 Machining	2016-01-29	2016-02-01	4	100.00%	Anthony, Jasdeep	
2.8 Mechanical Assembly	2016-02-02	2016-02-03	2	100.00%	Jasdeep, Ryan	
2.9 Milestone 1 Buffer	2016-02-04	2016-02-05	2	100.00%	All	Detailed Design Report
3.0 Milestone 3	2016-02-08	2016-02-26	19	87.50%		Design done in CAD.
3.1 Housing Design	2016-02-08	2016-02-10	3	100.00%	Jeremiah, Jasdeep	
3.2 Sensor Signal Conditioning Circuit Design	2016-02-08	2016-02-09	2	100.00%	Tian, Anthony	
3.3 Motor Control Circuit Design	2016-02-10	2016-02-11	2	100.00%	Anthony, Tian	Sensors and actuator layout and pin
3.4 Peripheral Management	2016-02-12	2016-02-12	1	100.00%	Tian, Jasdeep	
3.5 Electrical Design Review Meeting	2016-02-13	2016-02-13	1	100.00%	Tian, Ryan	
3.6 Finite State Machine Design	2016-02-08	2016-02-09	2	100.00%	Ryan, Blair	Research and develop search algorithm.
3.7 Search Algorithm Evaluation/Design	2016-02-10	2016-02-11	2	100.00%	Blair	Model motors to generate its responses.
3.8 Motor Controls Driver and API Design	2016-02-10	2016-02-11	2	100.00%	Ryan, Jeremiah	Typical movement the robot will take.
3.9 Movement Controls Driver and API Design	2016-02-12	2016-02-13	2	0.00%	Ryan, Jeremiah	
3.10 Sensor Signal Processing Algorithm and API Design	2016-02-12	2016-02-13	2	0.00%	Blair	Plans for testing the search algorithm.
3.11 Search Algorithm Test Plan	2016-02-14	2016-02-16	3	100.00%	Jasdeep, Blair	
3.12 Software Design Review Meeting	2016-02-17	2016-02-17	1	100.00%	Blair, Ryan	
3.13 Detailed Design Report	2016-02-18	2016-02-21	4	100.00%	Ryan	
3.14 Milestone 3 Buffer	2016-02-22	2016-02-26	5	100.00%	All	Construction Check #2
4.0 Milestone 4	2016-02-27	2016-03-04	7	8.33%		
4.1 Electrical Assembly	2016-02-27	2016-02-28	2	50.00%	Anthony, Jasdeep	
4.3 Hardware Verification	2016-02-28	2016-02-29	2	0.00%	Jasdeep	Integrate all drivers, fsm, and algorithms.
4.4 Software Implementation	2016-02-27	2016-02-28	2	0.00%	Blair, Ryan, Tian	Ensures that the software behaves
4.6 System Integration	2016-02-29	2016-03-02	3	0.00%	Jasdeep, Jeremiah	Field test (Includes buffer for milestone 4
4.7 System Level Testing	2016-03-02	2016-03-04	3	0.00%	Jasdeep, Tian	Presentation
5.0 Milestone 5	2016-02-29	2016-03-04	5	0.00%		
5.1 Design Post Mortem Meeting	2016-02-29	2016-02-29	1	0.00%	Ryan	Create powerpoint for presentation.
5.2 Design Presentation	2016-03-01	2016-03-04	4	0.00%	Ryan, Jeremiah	Competition
6.0 Milestone 6	2016-03-07	2016-03-10	4	0.00%		Additional field tests to work out edge
6.1 Test Runs	2016-03-07	2016-03-10	4	0.00%	All	

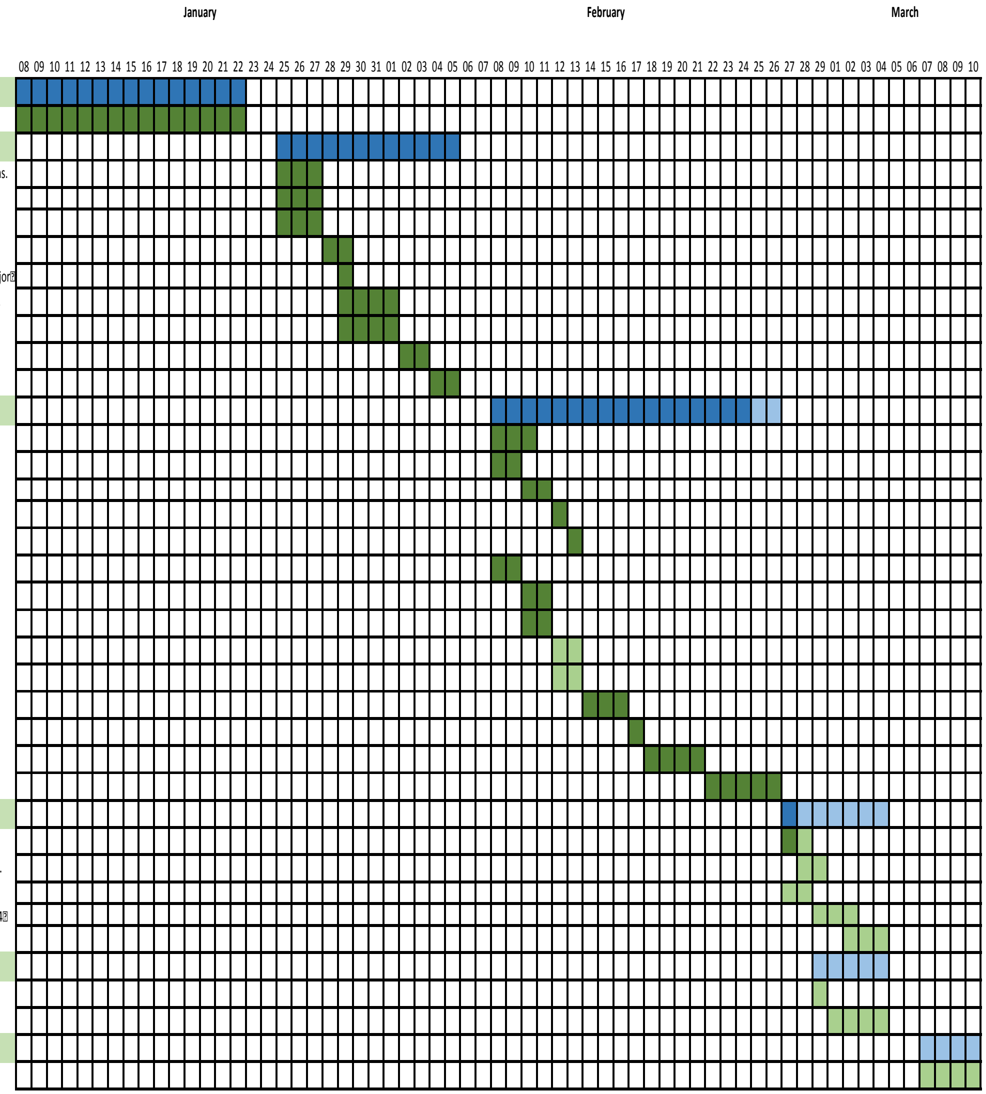


Figure 1: Gantt Chart

2.2 Deliverables

During the course of the project, there are several deliverables that must be completed. The deliverables are listed below in order of completion:

- Report #1 (January 22, 2016) - Proposal and Conceptual Design: outlines a work plan for the project that describes the activities and expectations of the team for the project. Included in this report are details about the conceptual design and the decision making process of the team that lead to the selected design.
- Construction Check 1 (February 5, 2016): completion of only the mechanical components of the design, so the body and chassis of the robot.
- Report #2 - Detailed Design (February 29, 2016): The second report includes a detailed design analysis of the design, material and part selection of the robot.
- Construction Check #2 (March 4, 2016): the vehicle is able to turn on and perform an action, such as moving on its own.
- Presentation (March 4, 2016): present the design analysis
- Competition (March 18, 2016): vehicle will perform its search and rescue while competing against other teams.
- Report #3 – Final (April 1, 2016): reflection of the final vehicle design in how it matches up to the objectives and constraints. Also, a discussion of the results from the competition.

2.3 Budget

In this section the budget is outlined to show how much money has been allocated for each component that needs to be bought for the design and the total should be equal or less than $215. The cost of labour is 0 because HUBRIS is a team made up of unpaid interns. The budget can be seen in Table 1 below.

Table 1: Budget Breakdown

		Cost Estimate 1 ($CAD)	Cost Estimate 2 ($CAD)
Hardware	Motor	22	85
	Enclosure	75	10
	Wheels	25	25
	Sensors	20	28
	Battery	10	20
	Circuit elements	20	40
Emergency	Extra parts	43	100
Labour	Interns	0	0
Total		**$215**	**$308**

The budget requirement for the project has been updated to reflect certain issues that were not considered in the initial report. The team had underestimated the torque requirement of the robot and as such more expensive motors had to be purchased. Initially, the team was going to design the enclosure, however to reduce costs, a general purpose enclosure was purchased instead for a lower price. The budget for the wheels selected initially remain the same as the wheels do not change. The budget for the battery and circuit elements have increased as the more powerful motor requires a lot more current than initially predicted. Lastly, the estimate for extra parts needed for the project also increased as extra parts were needed to assembly the unit to the enclosure. This brings the total budget to $308 dollars which is $93 more than the $215 budget initially provided.

3 Detailed Design

The previously selected general design was the solution involving using the ramp to travel over the mountain range wall on wheels. The following sections document the more detailed design decisions for the project. This is split into three components: mechanical, electrical, and controls.

3.1 Mechanical Design

This section provides the design reasoning for the mechanical design and the part selection. In addition, a torque specification is required to give to the electrical engineering team as an aid in motor selection.

3.1.1 Ramp Guiding Mechanism

One of the requirements for the design is that the robot must not fall off the ramp. While there are methods to achieve this using sensors, the controls team expressed a desire for a mechanical means of ensuring that the robot stays on the ramp. A mechanical mechanism for physical ramp guidance prevents total dependence on sensors and software at little foreseeable additional cost.

3.1.1.1 Theory of Operation of Ramp Guiding Mechanism Alternatives

Two design alternatives for the ramp guidance mechanism are considered in this section: a pivoting arm which clings onto the edge of the ramp, and a larger additional wheels that clamp the robot onto the ramp. Sketches of the two alternatives are shown below in Figure 2.

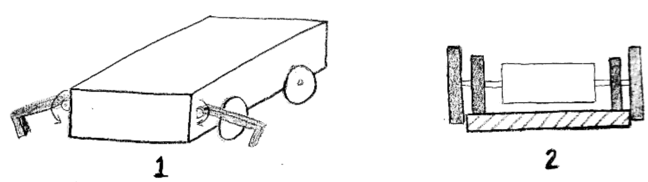


Figure 2: Ramp Guidance Mechanism Alternatives

The first method considered for ramp guidance involves an arm on the right and left sides of the robot that is in use only as the robot goes up the ramp. When the robot is on the ramp, a drive mechanism is required to lower the arms to wrap onto the underside of the ramp.

The second method considered is to have a two-wheel configuration as shown to the right in Figure 2 In this configuration, during normal operation on flat surfaces, the outer wheels are used. When going up the ramp, the calibrated distance between the outer wheels on the right and left sides prevents them from being used on the ramp. Thus the inner wheels are used, with the outer wheels functioning as guides to ensure the robot goes straight up the ramp without falling.

3.1.2 Evaluation of Ramp Guiding Mechanism

Based on considerations of the design criteria of cost, construction time, and mass, it is determined that the second method is the better option. With only four additional wheels, the cost is likely lower than the first option where materials for the arm as well as the motor for moving it are necessary. With the second option also being easier to implement, the construction time is greatly reduced. Finally, while the material of the additional wheels plays a factor, the second design will weigh less than the motor and arm mechanism.

3.1.3 Enclosure and Wheel Selection

With the general design of the robot's appearance decided, this section shows the selection process of an enclosure and wheels.

3.1.3.1 Enclosure

For the selection of an appropriate enclosure design, a decision is made between using a prefabricated enclosure or a custom manufactured one. The problems with making an enclosure include more time and money being spent. One of the goals for the project is that the time required to design and construct the vehicle should be kept low as possible. In order to reduce the risks in creating an enclosure, it is decided to use a store bought enclosure to ensure reliability, reduce costs and keep construction time to a minimum.

Now the dimensions of the enclosure are to be chosen. The vehicle is uses a two-wheel configuration on each axle, where the outer wheels clamp on the sides of the ramp. In order to accomplish this, the enclosure needs a width that is less than 152 mm. Also, the minimum width is 80 mm to ensure at least two motors can fit in the enclosure as each motor has a width of 40 mm. For the length and height of the enclosure, a conservative size is used, which is approximately double the dimensions of the Arduino Mega 2560. The maximum length is 200 mm and minimum height is 30 mm. The minimum height has to be changed to ensure that any motor chosen can fit. So a minimum height of 50 mm is chosen since motor heights are usually around 40 mm and using a bigger height can ensure any size of motor can fit and other electronic components can fit the enclosure. The minimum length that the enclosure has is 115 mm, to ensure that enclosure can fit the Arduino which has a length of 101 mm and have a bit of space between the parts in the enclosure. This ensures that there isn't a tight fit and it is easy to arrange the parts in the enclosure. After the dimensions and materials of the enclosure are decided on, a decision is made for where to buy the enclosure from. The decision is to use a local supplier that carried enclosures, which saves money on shipping and have enclosure faster. The common series at the supplier was the Hammond 1591 series enclosures and the enclosures didn't have holes for the shafts of the motors, so the enclosure needed to be made of ABS plastic, so it is easy to drill into and make modifications to enclosure if required later on. The biggest enclosure at the local supplier that had the dimensions required is the Hammond 1591E enclosure. The length, width and height of the enclosure used are 191 mm, 110 mm, and 57 mm.

3.1.3.2 Wheels

Based on the enclosure height of 57 mm and assuming that the axle of the motor is placed in the center of the side of the enclosure, a wheel is required that has a radius that is least 28.5 mm. This ensures that the enclosure isn't scraping against the floor. Looking at the plastic wheels with rubber tires from a local supplier, Creatron, the smallest radius of wheel that is available are 60 mm diameter wheels.

The vehicle uses an inner and outer wheel configuration to stay balanced on the ramp, so a wheel size is to be determined for the outer wheel. Looking at Figure 3 below where the vehicle is at the flat part of the ramp, the maximum difference between the inner and outer wheel is equal to the thickness of the wood, otherwise the outer wheels will get stuck by the mountain walls. The maximum difference is then 19.05 mm and gives a maximum radius of 49.05 mm. The wheels chosen for the outer wheel was selected to have a diameter of 80mm.

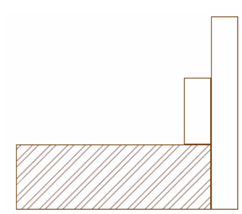


Figure 3: Wheel configuration on flat part of ramp

3.1.4 Torque

This section provides the calculations required to calculate the torque needed to climb the ramp. This will be used by the electrical team for the purposes of motor selection.

3.1.4.1 Explanation of Theory

The four motors used converts the current from the batteries into torque to turn the wheels and move the vehicle. A desired velocity can be used to determine the torque required. The focus will be on the torque required for the vehicle to move up the ramp because in the other cases the robot will be able to move with ease on the flat floor.

From Figure 4 below, the force of gravity acting in the x and y directions respectively are:

$$F_{gx} = mgsin(\theta)\ and\ F_{gy} = mgcos(\theta)$$

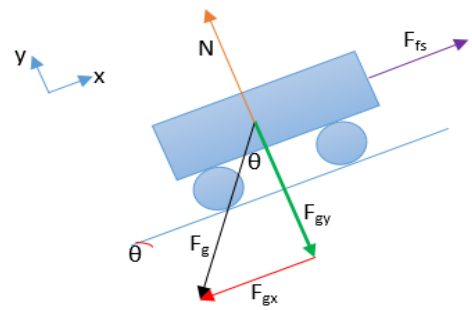


Figure 4: Free body diagram of the robot on the ramp

where g is the gravitational acceleration of 9.81 [m/s^2] and θ is the angle of the ramp with respect to the horizontal, which in this case is 30˚. For the robot to stay on the ramp, the acceleration in the y direction must be zero and we can solve for N, the normal force acting on the robot by the summation of forces in the y direction:

$$\sum F_y = ma_y = 0 \rightarrow N - F_{gy} = 0$$

$$\therefore N = mg\cos(\theta)$$

Similarly, for the robot move up the ramp it must move at a minimum at constant velocity—that is, where acceleration in the x direction is zero. The frictional force in this minimum allowable case can be found:

$$\sum F_x = ma_x = 0 \rightarrow F_{fs_{min}} - F_{gx} = 0$$

$$\therefore F_{fs_{min}} = mg\sin(\theta)$$

The wheels utilize static friction in order to move the vehicle up the ramp. However, static friction is only operational up to a certain maximum threshold of force before giving way to kinetic friction. The maximum static friction $F_{fs_{max}}$ is determined by the equation:

$$F_{fs_{max}} = \mu_s N \rightarrow \ F_{fs_{max}} = \mu_s mg \cos(\theta)$$

where μ_s is the coefficient of static friction between the wheel and the ramp. Therefore, the static frictional force is constrained by a lower and upper bound in order for the robot to move up the ramp successfully:

$$mgsin(\theta) \leq F_{fs} \leq \ \mu_s mgcos(\theta)$$

The frictional force on the wheels is F_{fs} , and the total torque of the motors is T. These two can be related to the wheel radius R by $F_{fs} = \frac{T}{R}$. Substituting and rearranging the final expression is:

$$gRsin(\theta) \leq \frac{T}{m} \leq \ \mu_s gRcos(\theta)$$

3.1.4.2 Torque Specification for Motor Selection

For this specific design, the parameters that are known are the gravitational acceleration 9.81 m/s^2, the tilt angle of the ramp θ, the radius R of the inner wheel that will be in contact with the ramp, and the coefficient of static friction μ_s. While the tilt angle of the ramp is specified to be 30° and the radius of the selected inner wheel is 30 mm as outlined previously, the coefficient of static friction was determined experimentally to be 0.878, using the test setup as detailed in Appendix A.

The only unknown is the mass, because not all the selected components are known. However, knowing the mass of the enclosure, wheel assembly, and Arduino, and estimating the mass of the other components, it is estimated that the mass of components excluding the motors is 0.7 kg. Separating the total mass m into the mass of the motors m_{motors} and the mass of the other components $m_{other} = 0.7\ kg$, and substituting all parameters into the inequality, the requirement becomes:

$$0.14715 \leq \frac{T}{m_{motors} + 0.7} \leq \ 0.22378$$

Simplifying to reduce for the torque and mass of each individual motor out of the four total:

$$0.14715 \leq \frac{4T_{motor}}{4m_{motor} + 0.7} \leq 0.22378$$

where mass is in kilograms and torque is in Newton-meters. A graphical representation of this torque-mass requirement is shown below in Figure 5.

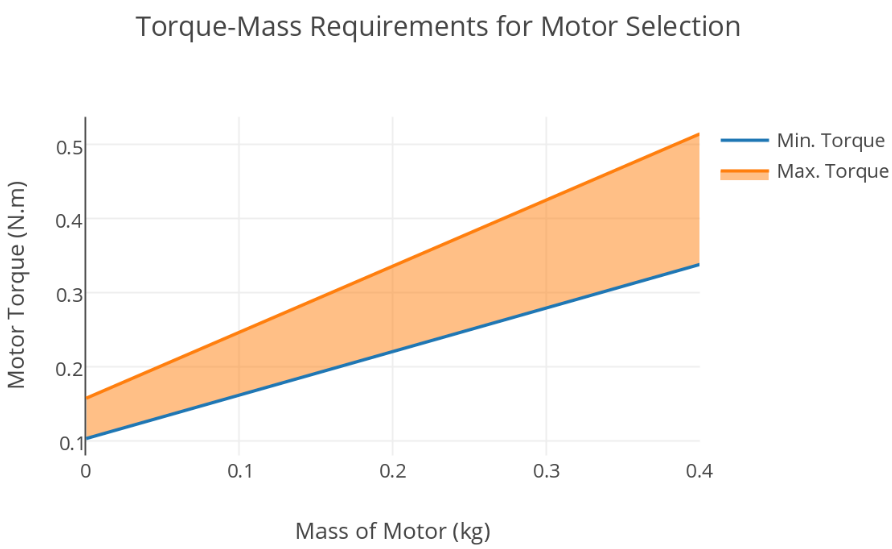


Figure 5: Torque-mass requirements for motor selection

Therefore, any motor with a mass and torque combination within the shaded region will be allow the robot to travel up the ramp without slippage.

3.2 Electrical Design

This section provides the analysis and evaluation of electrical design decisions leading up to the selection of parts used in the final design.

3.2.1 Drive Mechanism

This section provides the analysis and evaluation of electrical design decisions made in selecting electrical parts needed for the drivetrain to allow for propulsion.

3.2.1.1 Motor Selection

This section will outline the motor selection process in accordance with the weight and torque calculations specified in Section 3.1.4.2 above.

3.2.1.1.1 Defining Motor Specifications

The motor specifications have been defined by the controls and mechanical team. Table 2 below outlines the criteria and constraints for motor selection.

Table 2: Motor Criteria and Constraints

Motor Criteria	**Motor Constraints**
Maximize Precision (ideally higher precision than distance sensor)	Meet Torque - Mass criteria (Figure 5)
Minimize Current Draw	Meet Volume Constraints of Enclosure
Minimize Mass	Must have continuous rotation
Minimize Cost	Must be attainable within project timeline

3.2.1.1.2 Theory of Operation of the Different Motor Alternatives

The types of motors considered for this project are determined based on their availability in common electronics distributors with acceptable lead time (lead time < 1 month). These motors included Stepper Motors, DC Motors and Servos.

A DC Motor is a motor that allows continuous rotation when voltage is applied to it’s two wires (Power and Ground). DC Motors generally run at high RPM but have lower torque and can be controlled by applying a Pulse Width Modulation (PWM) input to control the velocity of the motor.

Servos are DC Motors with a gearbox and a form of feedback (generally a control circuit and a potentiometer). Servos generally have higher torque than standard DC motors and allow for closed loop feedback as opposed to running the motor in open loop (DC motors). However, because a potentiometer is attached to the output shaft (for position feedback) general purpose servos are limited to how much the potentiometer can rotate; which is generally less than 180°. Servos can also be controlled using a PWM signal, but unlike DC motors, the PWM signal is used to control the position of output shaft.

While DC Motors and Servos, rely on energizing a single coil to allow for rotation, Stepper motors have a system of coils/electromagnets around a central shaft that are energized in an alternating pattern. Each phase in the pattern will align the central shaft to one of the coils, while being slightly offset from the other coil. Controlling which coil is energized at a point in time allows the shaft to rotate. Steppers require an external control circuit that will alternate the order of energizing the coil in such a way that the shaft can be commanded to move to a specific position (in other words commanded to go a certain number of steps). Stepper motors are not limited to a degree of rotation, or in other words, like DC motors, they have the ability to rotate continuously.

3.2.1.1.3 Evaluating Specific Motor Selection

In order to meet the design constraint of continuous rotation, the servos selected would have to be modified to allow for continuous rotation (also known as continuous servos). Continuous servos forgo the potentiometer (used for position feedback) limiting the rotation of output shaft, and are essentially geared DC motors that take in a PWM input to control the position.

The three types of motors selected above meet all the design constraints of the project. Table 3 below outlines the decision making process in determining which type of motor would be selected. The scores below are determined by comparing data from different types of motors obtainable from Robot Shop in Figure 5. The precision was quantified by assuming that since the DC motor and the continuous servo operate on essentially the same principle and are much less precise than steppers, they are given the lowest score possible. The decision matrix below in Table 3 compares the different motors that operate on the required torque range.

Table 3: Motor Decision Matrix

	Precision (10)	*Mass (4)*	*Cost (4)*	*Normalized Total*
DC Motor (RS-555 12V 7750 RPM Brushed) [1]	1	2 (213g)	4 ($8.50)	0.389
Continuous Servo (HSR-1425CR)[2]	1	4 (41.7g)	1 ($22.30)	0.333
Stepper (12V 0.4A 36oz-in Unipolar)[3]	10	1 (280g)	1 ($21.01)	0.66

Precision has the highest weighting as it is essential that the robot be able to have a high degree of precision to be commanded to get on the ramp. Although there is an element of position feedback implemented in final design, a high precision motor will allow for more control

The precision of the Servo and DC motor can be increased by attaching an encoder to the shaft, however this adds an element of complexity in construction of the robot that goes against the criteria of decreasing construction time. The introduction of an encoder also slightly increases the cost of the project. However, the DC Motor/Servo with an encoder does offer a severe mass reduction. Therefore, it was decided that the potential decrease in mass was not worth the increase in construction time, hence the stepper motor was selected.

Mass was given a lower weighting as although it is incorporated into the final score, it was considered an acceptable tradeoff in order to ensure high precision. Cost was given an equivalent weighting to mass as it’s price would be a big subset of the final project cost. However, a substantial increase in cost would not justify a substantial improvement in mass, in other words their values are treated as equal. On the other hand, a higher cost would be acceptable to ensure high precision.

The decision to select the Soyo 2 Phase 6-Wire Unipolar Stepper motor specifically was largely determined by its precision, cost and lead time/availability of the motor. Refer to Table 4 below for the specific parameters of the stepper motor.

Table 4: Important Data Sheet Parameter of Soyo Stepper Motor

Step Angle	1.8º
Step Accuracy	±5% (full step, no load)
Rated Voltage	12V
Current/Phase	0.4A/Phase
Motor Type	6-Wire Unipolar Stepper
Holding Torque	0.254 Nm
Cost	$ 21.01

This specific motor met all the torque and volume constraints of the mechanical team, while also being precise enough to satisfy the requirements of the controls team (200 steps/revolution). The precision of the motors would be higher than that of the distance sensor used to determine close loop feedback, hence it was deemed acceptable. This coupled with the fact that it was within the budget allocated for motors and it was readily available for the construction check is why the motor was selected.

3.2.1.2 Motor Controller Selection

The section below introduces the need for a dedicated motor controller to drive the stepper motor selected above. This section also outlines the different motor controllers selected and a brief explanation of the motor selection.

3.2.1.2.1 Explanation of Theory

A motor controller is needed to properly control the order of which the coils are energized (stepping the motors) while also supplying an appropriate amount of current needed to drive the motor. By default, the Arduino Mega R3 is unable to drive the steppers motor needed for the project as is unable to provide sufficient current to drive the motor at 12 V and 1.6 A (4 Motors @ 400mA/motor). Figure 6 below outlines the power supply of the Arduino Mega, where "the *regulator output current must not exceed 1.0 A with Vin greater than 12 V"* [4][5].

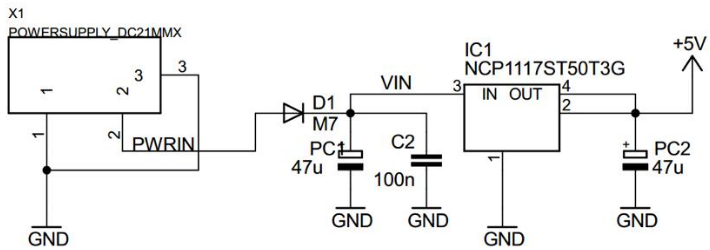


Figure 6: Power Supply of the Arduino Mega R3

In order to drive and step the motors using significantly less current, an H-Bridge is used to abstract the process of supplying power to the motor through a system of transistors that will handle the switching application. The Arduino would simply switch the transistors on/off allowing connect the motor to the supply through the transistors (not the Arduino itself). Figure 7 below shows a rough schematic of configuring an H-Bridge using transistors.

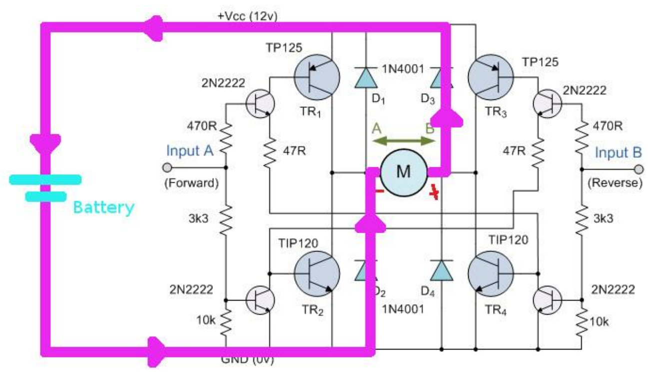


Figure 7: H-Bridge Example [6]

Switching TR_2 and TR_3 on and switching TR_1 and TR_4 off allows current to flow in the direction signified in purple. This configuration would significantly reduce the current requirement needed from the Arduino as it is no longer supplying current needed to drive the motor, simply to switch transistors. The H-bridge would be connected to a single coil of the motor. Since the motors selected are 2 Phase Unipolar Stepper Motors, each motor would require two H-Bridges to drive both coils, resulting in eight H-Bridges needed in total. Also present in Figure 7 above are Flyback Diodes (D_1 – D_4) that provide an appropriate path for current to flow when the motor is suddenly switched off (recall that motors are an inductive load and cannot change current instantly). These diodes allow for the motors to properly be switched on and off without damaging the rest of the circuit by providing a path for the reverse current to flow when the motor is switched off.

3.2.1.2.2 Evaluating Alternatives

The motor controller to be selected have the design constraints outlined in Table 5 below.

Table 5: Motor Controller Constraints

Number of Total H-Bridges	2 coils * 4 motors = 8 H-Bridges Total
Output Current (single H-Bridge)	400 mA/phase
Supply Voltage	12V
Output Voltage	12V
Flyback Diodes at Power Transistors	Yes
Package for Arduino Mega R3	Compatible Arduino Motor Shield

The first five constraints listed above had been defined in accordance with the specification of the stepper motors. Only motor shields were considered instead of a set of motor controllers to avoid having to connect multiple controllers to each motor and connecting these controllers to the Arduino. Installing a shield onto the Arduino itself reduces the amount of physical wiring jobs that have to be made, increasing simplicity, reducing construction time and preventing any potential wiring errors. The slight increase in cost of the motor shields compared to the individual motor controllers was deemed such an appropriate tradeoff that it was defined as a constraint.

The stringent design constraints limited the availability of motor shields available to be procured within an appropriate lead time to allow the team to meet the construction check deadline. The design criteria used to decide between motor shields were reduction of construction time and cost. Two motor shields were considered the Adafruit Motor Shield [7] and the iTead Studio Motor Shield Driver [8]. Both motor shields did not meet the design constraint of total number of H-Bridges. However, both motor shields allowed for stackable design with each shield addressable via I^2C. The iTead Studio motor shield was slightly more affordable ($5 dollars less), however the Adafruit Motor Shield provides a significant amount of software libraries that abstracts interfacing with the stepper motor. This would significantly reduce the time needed to get up to speed to interface with the motor. The Adafruit Motor Shield also has a significant community following online that would help reduce debugging time should issues occur, assuming these are similar issues the community has encountered. The potential decrease in construction time was worth the tradeoff of a slight increase in cost. Table 6 below shows some the specifications of a single Adafruit Motor Shield and outlines how it meets the design constraints listed above. Note that two motor shields will be stacked on top of each other using the I^2C bus to properly address the appropriate motor shield.

Table 6: Comparing Adafruit Motor Shield Specifications With Design Constraint

	Design Constraint	**Adafruit Motor Shield**
Number of Total H-Bridges	2 coils * 4 motors = 8 H-Bridges Total	2 shields * 4 H-Bridges/Shield = 8 total
Output Current (single H-Bridge)	400 mA/phase	1.2 A/motor (average) 1.5A/motor (peak)
Supply Voltage	12V	12V
Output Voltage	12V	12V
Flyback Diodes at Power Transistors	Yes	Yes
Package for Arduino Mega R3	Compatible	Compatible

3.2.2 Sensor Selection

The controls team required a set of sensors to allow for feedback control to be used in the path finding and base detecting algorithm. These sensors include a form of a distance sensor as well as an accelerometer and gyroscope. The design constraints for the sensors were specified by the controls team. For simplifying the comparison process, all the parts considered below are parts available from RobotShop that can be attainable within an acceptable lead time (<1 week). Please note that the mass of the sensors was neglected as the mass of the sensors considered were all less than 10g, relatively insignificant compared to the mass of the other parts on the robot (motors = 1.6kg). The section below will outline the design criteria and constraints used to determine the sensor to be used by evaluating a range of plausible sensors.

3.2.2.1 Distance Sensing

The two design constraints defined by the controls team is that the sensor be able to detect the distance between the robot and an object in front of it, and that it be small enough to be mounted on the robot. The design criteria for the distance sensor is to maximize sensing precision, maximize reliability and repeatability of distance measurements while minimizing cost. The available distance sensors on RobotShop include Ultrasonic Sensors and Infrared (IR Sensors).

3.2.2.1.1 Theory of Operation

Both ultrasonic sensors and infrared sensors rely on an emitter-receiver principle, where the time between emitting a wave and it bouncing back off the object of interest back to the receiver is correlated with the distance between objects. They differ in that ultrasonic sensors rely on emit a sound wave, while IR sensors emit IR waves. Therefore, waves emitted by the ultrasonic sensor are emitted in a cone like shape see Figure 8 below.

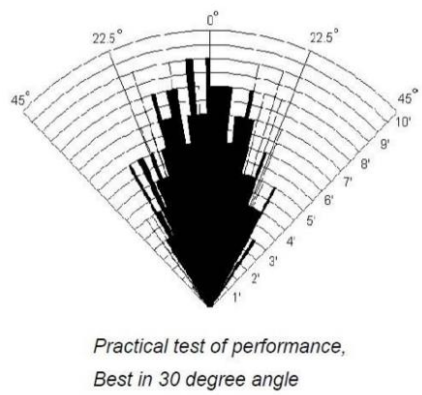


Figure 8: 30 Degree Detection Angle for the Ultrasonic Sensor (HC-SR04) [9]

While waves emitted from the IR sensor are a lot more direct. This means that the IR sensor is more accurate in detecting distance between two points, the ultrasonic sensor will report the closest object within the cone emitted. However, IR sensors are more susceptible to noise as it is sensitive to other frequency or rays in the electromagnetic spectrum. It is important to note that both sensors struggle with detecting objects that are not directly perpendicular to the sensor (object is on an angle) as the wave will not be reflected back to the emitter or will be reflected back with a time offset.

3.2.2.1.2 Evaluating Alternatives

The most popular IR and Ultrasonic sensor obtainable from Robot Shop have been listed below in Table 7.

Table 7: IR vs Ultrasonic Sensor

	IR Sensor: **Sharp GP2Y0A60SZ** [10]	**Ultrasonic Sensor:** **iTead Studio HC-SR04** [11]
Precision	10 – 150 cm	2cm – 200cm
Reliability	Low	High
Cost	$12.26	$3.99

The IR Sensor was given a low reliability score because it is more perceptible to it's the change in lighting of it's environment. Without any filtering this would result in a low repeatability and reliability. A decision matrix was not created to decide between these two components as the ultrasonic sensor is the clear winner in each criterion, it has better precision, is more reliable and cheaper. The downside of the ultrasonic sensor is that due to the larger detection angle any object within the cone in Figure 8 might be detected though it is not the object of interest. However, this is easier to compensate for in software than applying significant filtering in the IR sensor.

Specifically, the HC-SR04 was the ultrasonic sensor selected because in addition to being precise, relatively reliable and low cost, it is also very commonly used sensor with multiple library support online of which the team has experience interfacing with. This will serve to reduce time needed to get up to speed with the sensor, reducing construction time.

3.2.2.2 Ramp Sensing

Sensing the ramp requires a sensor that is capable of detecting the orientation of the robot. The ideal component should be small, have an accelerometer and/or a gyroscope as well as an easy to use interface. The best sensor for the job is an inertial measurement unit (IMU) as they are small, contain both an accelerometer and a gyroscope and have built in libraries for easy interfacing with an Arduino. Due to the slow moving nature of the robot, the controls team did not see a need for any specialized high accuracy IMUs. The best course of action would be to find am IMU that is affordable and easy to use. Since many of the other parts were selected from Robot Shop's inventory, it makes sense to purchase the IMU from the same place. The cheapest IMU on Robot Shop is the MPU6050 [12]. A summary of the features is listed in Table 8.

Table 8: Electric Properties of the MPU6050

Working Voltage	3-5 V
Current Draw	3.9 mA
Sensors	Accelerometer, Gyroscope
Interface	I^2C

The MPU6050 may be one of the most basic IMUs but it is more than enough for the purpose of ramp sensing. It contains both an accelerometer and a gyroscope and has built in I2C libraries for easy interfacing with the Arduino. Furthermore, the working voltage and current draw are well within the limitations of the power supply which means that it is the best choice for the job.

3.2.3 Power

The following section outlines the decisions involved in selecting a power supply based on the power consumption of the robot.

3.2.3.1 Explanation of Theory

In order to properly build an independent robot, a portable power supply must be chosen over a non-portable alternative. Furthermore, the size constraint of the robot means that smaller sources are much more suitable for the job. The system requires 12V to properly power and needs to last long enough to traverse to the destination with a large margin to spare.

Two methods were considered when deciding on the method to achieve the necessary 12V required for the system. The first and simplest method that was considered is using a 12V battery pack. The second method is using the combination of a lower voltage battery and a boost converter to reach the necessary 12V.

3.2.3.2 Power Requirements

In order to decide on a battery pack, the power requirements need to be found. It has already been established that the required voltage is 12V but the current must be calculated to determine the lowest voltage source that can be used to generate 12V with a boost converter. It is also required to determine how long a supply will last under the load.

To determine the current usage, the individual usage of each peripheral can be added together. The stepper motors are rated for 400 mA per phase so in a two phase motor, 800mA draw is the worst case scenario. The worst case scenario for the other peripherals is the current draw when they are in use. Table 9 below depicts the current draw of the components

Table 9: Current Draw of Robot Components

Peripheral	Current Draw	Quantity	Total Current Draw
Ultrasonic	15 mA [9]	4	60 mA
Stepper Motor	800 mA [13]	4	3200 mA
MPU	3.9 mA [14]	1	3.9 mA

The total current draw is 3263.9 mA which is a very large current draw. A boost converter would have a hard time boosting the voltage to 12V in this scenario unless the input voltage was already close to 12V. After running simulations in LTSpice to boost various voltage supplies to 12V, it is found that 9.1V is the minimum voltage required from the supply to output the necessary current at the 12V level. Figure 9 shows that a 9.1V supply is able to provide the necessary current while Figure 10 shows that a 9V supply is unable to reach the necessary current level.

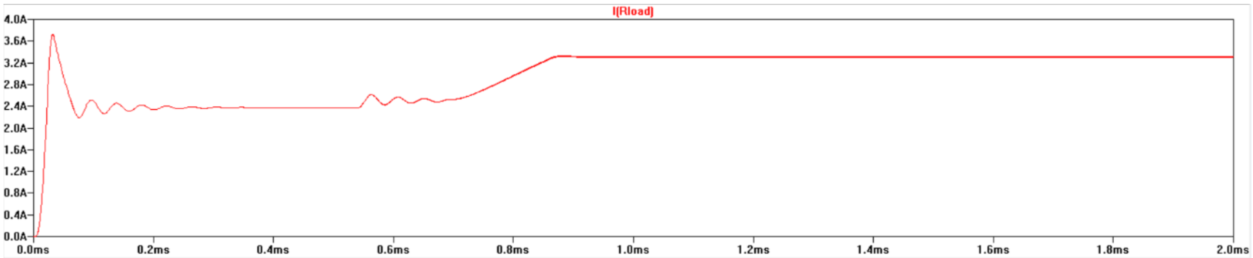


Figure 9: Drawing 3263.9 mA of Current from a 9.1V to 12V Boost Converter

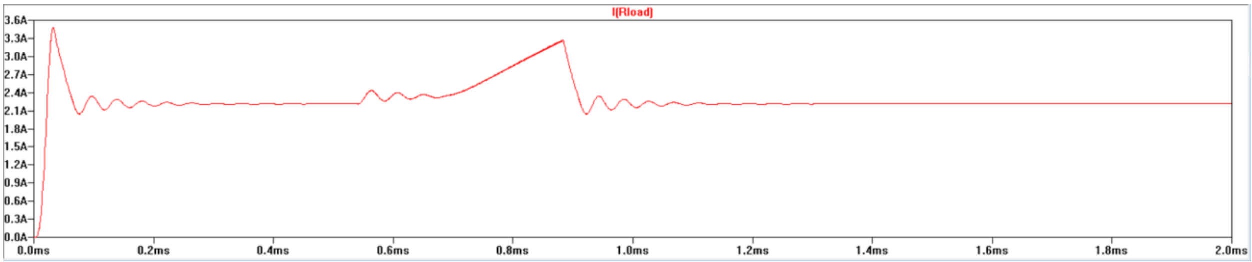


Figure 10: Drawing 3263.9 mA of Current from a 9V to 12V Boost Converter

Any lower voltage source is unable to hold the current to the necessary level. Unfortunately, 9.1V battery packs are very rare so the more common 9.6V battery is suitable as an alternative. This also increases the margin of allowable error for the current draw. Table 10 compares the batteries:

Table 10: Comparison between 12V Battery and 9.6V battery Boost Converter System

	9.6 V Battery Pack and Boost Converter Combo [15]	Boost Converter [16]	12 V Battery Pack [17]
Charge	1600 mAh	N/A	1600 mAh
Mass	0.200 kg	N/A	0.251 kg
Price	$42.45 CAD	$6.66 CAD	$41.03 CAD

In a direct comparison of quantitative properties, it can be seen that the 9.6V battery and boost converter combination is fairly similar to the 12V battery. Not only is the difference in the charge non-existent, the mass and price differences are negligible.

The reason the 12V battery pack was chosen as the power supply of choice is because it allows for the most simplistic design and therefore minimizes risks with the full system. This benefit is very difficult to quantify but adding a boost converter would require far more work which would include the design of a voltage boosting system, acquiring SMD components to build the system, soldering components on a new board and integrating the board into the existing system.

Figure 11 and Figure 12 depict the difference in complexity between the 9.6V battery pack and boost converter compared to having the 12V battery pack. It is very clear to see that boost converter requires much more work and poses a much higher risk of causing problems with the operation of the robot.

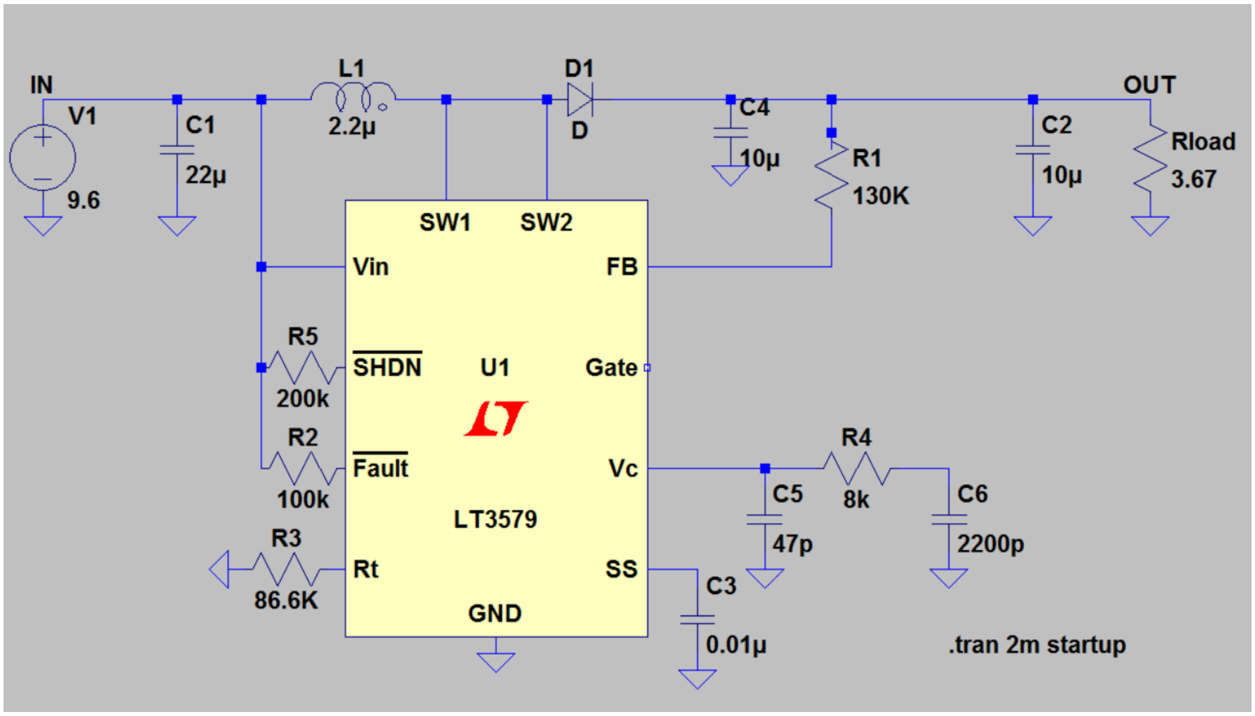


Figure 11: Schematic of 9.6V Battery and Boost Converter System

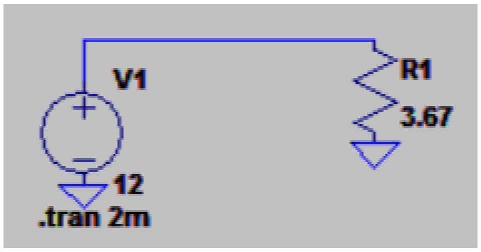


Figure 12: 12V Voltage Supply

The voltage and current values in Figure 13 to Figure 16 show that the 12V battery pack is already 12V in nature so it will output a perfectly flat signal when the robot is running. In contrast, the boost converter has inductance and capacitance in the system that causes a delay of around 1ms before settling into the correct transient state. Although the transient state is too short to noticeably affect the performance of the robot, the use of a lower voltage supply increases the risk of power failure when a sudden spike in current draw occurs.

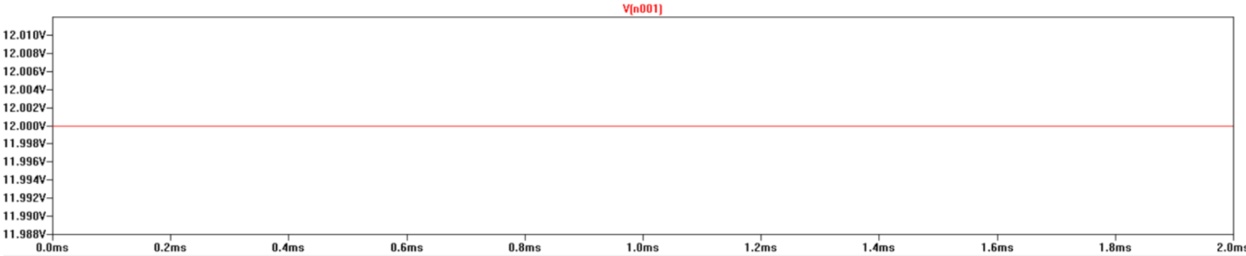


Figure 13: 12V Battery Voltage Level under Full Load

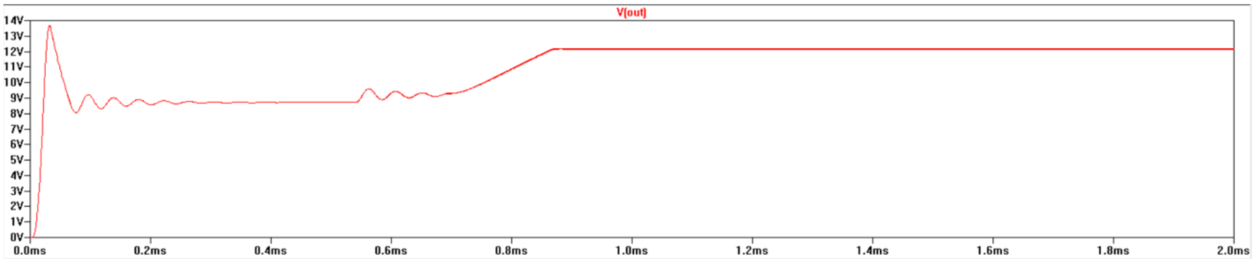


Figure 14: 9.6V Battery and Boost Converter Voltage Level under Full Load

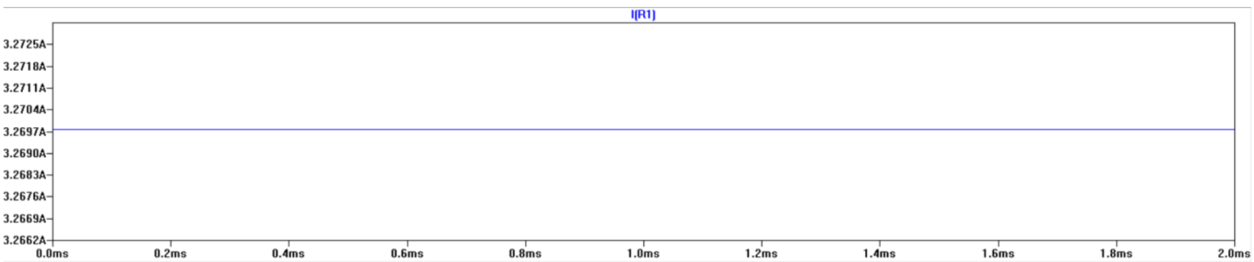


Figure 15: 12V Battery Current Level under Full Load

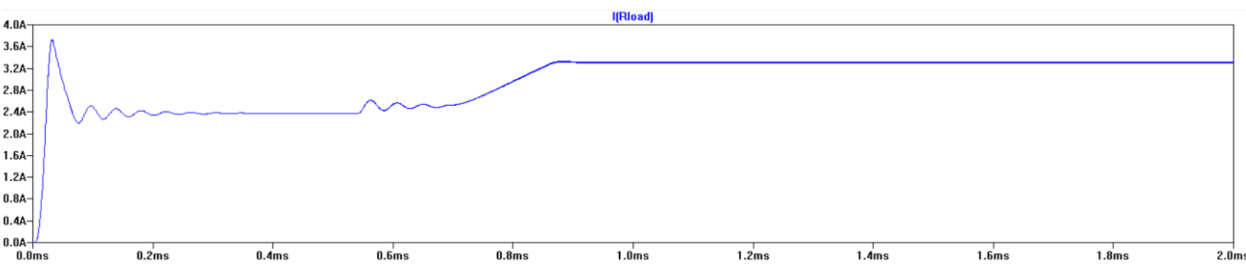


Figure 16: 9.6V Battery and Boost Converter Current Level under Full Load

3.3 Control System Design

The following section documents the design decisions made regarding the controls aspect of the robot. For flexibility, control algorithm design has been abstracted to avoid implying specific electrical or mechanical solutions where possible.

3.3.1 Overview of System Functional Tasks

From a high-level perspective of the actual functions of the robot design, there are several distinct, sequential tasks to accomplish, which are effectively derived from the key design problems discussed in Section 1.3.6. A flowchart depicting these functional tasks is shown in Figure 17 below.

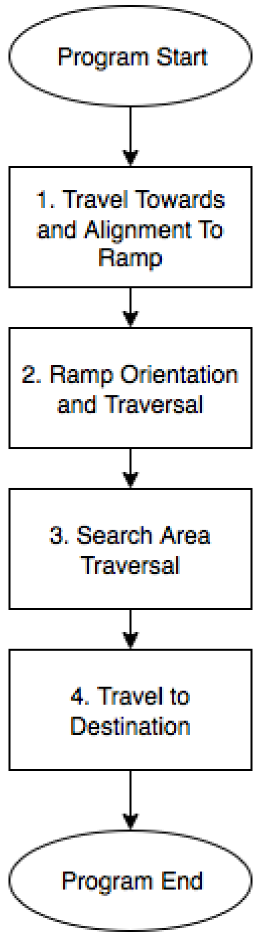


Figure 17: Functional Task Flow Chart

More specifically, the first task involves determining the location of the ramp, and the process of traveling towards the ramp such that when the robot arrives at the base of the ramp, its orientation is approximately collinear with the center of the ramp. The second task consists of correction for misalignment with the ramp until all of the inner, small wheels of the robot are making contact with the ramp, at which point it is to travel over to arrive at the ramp base on the opposite side. The third task involves traveling around the search site such that the robot is eventually able to detect and determine the location of the destination base relative to itself. The final task involves converging upon and moving to the location of the destination base.

Traversal to the ramp and traversal within the search area can both be achieved through determining the robot's location in the environment, which is therefore to be accomplished via a distance sensing algorithm. Ramp orientation and traversal is mainly concerned with remaining on the ramp in a straight orientation.

3.3.2 Distance Sensing Algorithm

The objectives for the distance sensing algorithm are mainly relevant to identifying the robot's orientation and position relative to some reference object(s) in the environment and identifying how movement can be controlled or directed to achieve a desired or commanded relative orientation and position. When this algorithm is applied during the task of traveling to the ramp, its role is to minimize the difference between the current distance from the robot's center to the center of the ramp, as well as the angle between the robot's trajectory and the center of the ramp. In a similar manner, when the robot is performing the task of searching for the base in the specified search area, the algorithm's function is to minimize positional error and angular deviation from a pre-planned path as it travels through the area, until the base has been detected.

3.3.2.1 Sweeping Algorithm

The sweeping algorithm involves mapping the surroundings with one distance sensor that sweeps separately in front or with the robot. During the sweep, multiple measurements are made to create a representation of the objects and obstacles that are in front or around it. Based on this information, the distances to the surrounding objects is mapped and can be used to guide the robot within the confined perimeter. In Figure 18 below, the geometry to calculate the distance between an object and the robot is shown. This assumes that the sensor sweeps together with the robot.

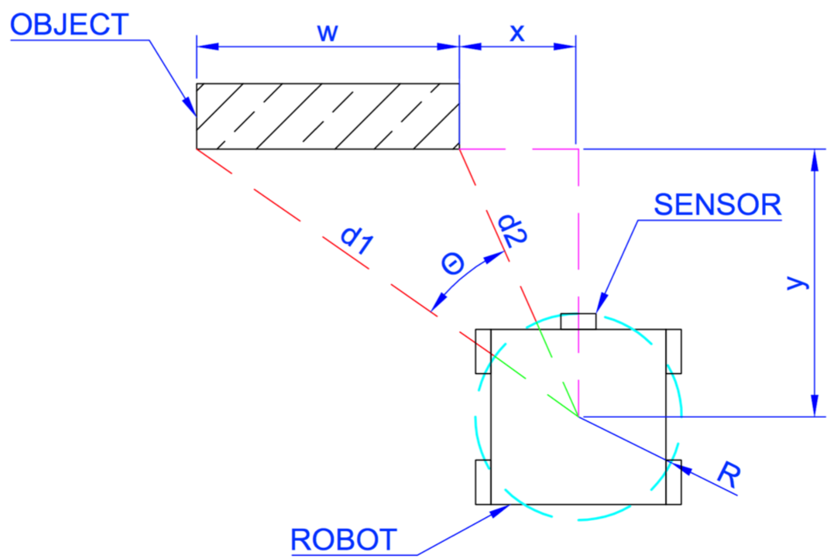


Figure 18: Sweeping Algorithm Diagram

From the above, the distance of the robot from the object in the x direction and y direction can be evaluated from the two edge distance inputs (d1 and d2) and the known rotation angle (θ) from the object. The two relations are stated below:

$$y = \frac{(\mathrm{R}+\mathrm{d}_1)(\mathrm{R}+\mathrm{d}_2)\sin(\theta)}{(R+d_1)^2+(R+d_2)^2-2(R+d_1)(R+d_2)\cos(\theta)}$$

$$x = \sqrt{(R+d_1)^2 - y^2} - [(R+d_1)^2 + (R+d_2)^2 - 2(R+d_1)(R+d_2)\cos(\theta)]$$

Based on this information, the robot is able remain within the perimeter of the competition and identify the ramp. In addition, by pre-mapping the expected map data on the other side of the mountain, any discrepancies and be attributed to identifying the targeted base.

3.3.2.2 Boundary Offset Algorithm

The boundary offset algorithm relies on both the robot's location relative to the boundary walls and its forward heading angle with respect to the walls. There are two main underlying assumptions to this algorithm: that the boundary walls are reasonably straight (no more than approximately 5 degrees of angular deviation per meter of boundary length), and that the boundary walls are close to parallel to the ramp (no more than approximately 5 degrees of angular deviation from a line parallel with the ramp's center in 1 meter of the boundary wall leading up to the ramp).

Defining the direction of the search area on the opposite side of the mountain range wall as north, the east boundary wall is selected as a reference when traveling to the ramp. Therefore, the reference distance measurements are always to be taken from the robot's right-facing side (i.e. the direction 90 degrees clockwise from its forward traveling direction), both when traveling to the ramp and when searching the area on the opposite side of the mountain range wall. Two reference distance measurements are necessary in order to determine both angular orientation and shortest distance with respect to the reference boundary edge. Taken in conjunction with the dimensions of the robot, this information can then be used to compute both the shortest distance from the center of the car to the closest reference boundary edge detected on the robot's right-facing side, and its angular orientation with respect to that boundary edge, where the former is based on an average of the two distance measurements and the latter is based on the difference of the two distance measurements. This configuration is shown in Figure 19 below.

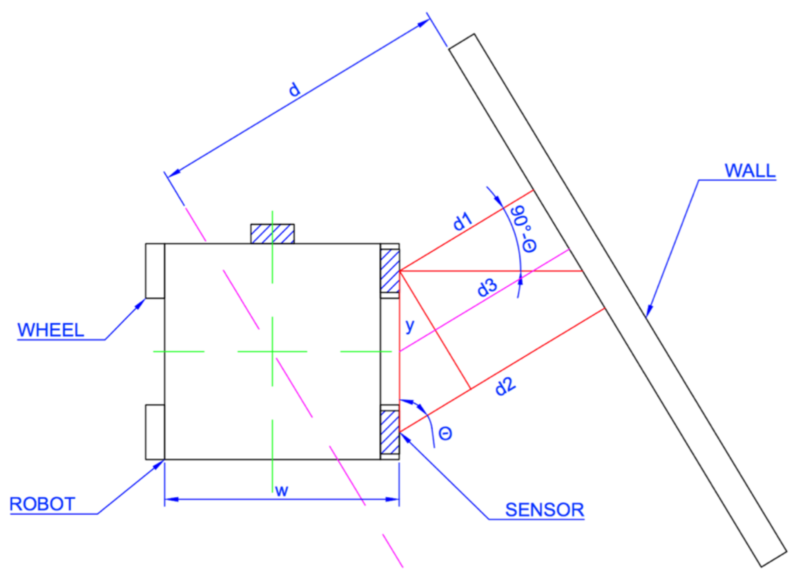


Figure 19: Boundary Offset Algorithm Diagram

Based on the above configuration, the distance (d) and the angle (θ) can be calculated based on the input distances (d1 and d2). The two relations are stated below:

$$d = d_3 + \frac{w}{2}\sin(\theta) \qquad where\ d_3 = \frac{d_1 + d_2}{2}$$

$$\theta = \cos^{-1}(\frac{d_1 - d_2}{y})$$

3.3.2.3 Distance Sensing Algorithm Evaluation

One of the main design criteria relevant to the selection of a distance sensing algorithm is execution time. However, there is inherent difficulty in accurately estimating the run time of each alternative prior to actually implementing them, thus a more generalized, qualitative approach is taken to compare the execution times. The sweeping distance sensing algorithm is concluded to require significantly more time to acquire the same relative position and angle data, as it requires additional rotations between non-simultaneous distance measurements, as opposed to the boundary offset distance sensing algorithm, which can obtain both of its measurements simultaneously and without additional movement. This corresponds to an increase in overall execution time for the sweeping algorithm, both during travel to the ramp and the search for the destination base.

The simultaneity of the distance measurements required by the boundary offset algorithm carries the disadvantage of requiring an additional sensor, which corresponds to an increase in the overall device's weight. However, this increase is insignificant in magnitude compared to the other components as discussed in Section 3.2.2 thus this is considered to be an acceptable tradeoff for the decreased execution time. In addition, assuming no change in the amount of sensor data processing and filtering between the two distance sensing algorithms, there is intuitively some additional uncertainty added by the sweeping algorithm, as the intermediate rotation of the robot between sensor measurements introduces the possibility for some small error due to wheel slipping or small position changes. As a result of the general overall benefits of the boundary offset algorithm, it is selected over the sweeping algorithm for the purposes of distance sensing.

3.3.3 Ramp Securing Algorithm

The purpose of the ramp securing algorithm is to detect and correct for initial misalignment of the robot's appropriate wheels with the ramp such that it travels up the ramp on the smaller wheels and uses the larger wheels as supporting guides. This is only applicable during the initial transition onto the ramp, after which it is assumed that the mechanical solution of staggered wheel sizes will be sufficient to keep the robot's trajectory on the ramp in the correct direction. Regardless of the ramp securing algorithm selected, the direction of misalignment must be identified, after which the robot is to drive in reverse until completely off of the ramp, before correcting its orientation slightly based on the misalignment and attempting to climb the ramp once more, repeating until no misalignment is detected. This incremental repetition is to ensure precision, as the small width of the wheels allows for easy overshoot.

3.3.3.1 Tilt Detection Algorithm

The basis of the tilt detection algorithm is the rather intuitive detection of tilt about its central forward facing axis, also known as roll. Upon detection of non-negligible roll, the robot is simply to reverse until off of the ramp, shift over in the direction opposite of the roll detected, and retry climbing the ramp.

3.3.3.2 Motor Current Monitoring Algorithm

The motor current monitoring algorithm relies upon the physical principle that motor torque is proportional to current draw. As the robot initially climbs up the ramp, misalignment of the appropriate wheels with the ramp will lead to either one of the front wheels losing contact with the ground, causing a significant decrease in the torque applied to the corresponding motor and therefore significantly reduced current draw through that motor. As with the tilt detection algorithm, the robot is to reverse off of the ramp and shift in the direction opposite of the side where reduced current was detected before re-attempting to climb the ramp.

3.3.3.3 Ramp Securing Algorithm Evaluation

The most significant difference of importance between the two algorithms is related to design and construction complexity. Motor current monitoring requires current draw sensing on both of the front motors, whereas tilt detection merely requires monitoring of roll of the robot as a whole, meaning that the tilt detection algorithm necessitates less sensors in the design, and also thereby eliminates any error from unequal noise or measurements in the case of multiple sensors. Furthermore, current sensing implies a need for additional circuitry components such as a sense resistor to measure the voltage across, while the tilt detection algorithm can work directly off of the roll measurement given by a sensor such as a simple gyroscope. As a result, the tilt detection algorithm is selected as the superior alternative.

3.3.4 Destination Base Detection Algorithm

The destination base detection algorithm is to be applied in parallel with the distance sensing algorithm when the robot is in the process of searching for the destination base on the opposite side of the mountain range. Its purpose is to detect the existence of the destination base and subsequently to provide information regarding the base's location and how the robot is to travel there.

3.3.4.1 Reference Distance Data Comparison Algorithm

The reference distance data comparison algorithm reuses the concept of distance sensing to determine when the destination base is detected. Assuming the robot is also simultaneously using the boundary offset distance sensing algorithm described in Section 3.3.2.2, two distance measurements will be constantly taken on the right-facing side of the device. Taking a distance measurement from the rear side of the robot will not be particularly useful for detecting the base, as the collected data would only be relevant to regions where the robot had previously traveled. Therefore, distance measurements will be taken from the front and left-facing sides of the robot.

The basis for the reference distance data comparison algorithm is the underlying assumption that the entire search and rescue site area will not physically change over time to any non-negligible extent. Based on this assumption, this algorithm involves first running a series of pre-execution runs, in which the robot is to travel along a pre-planned path around only the search side of the mountain range wall, where the destination base has first been removed, and collect a series of distance measurements from its front and left-facing sides as it travels for each run. The number of runs to repeat must be significant (at least 30), and the distance measurements taken will be averaged and filtered across the various runs to remove outlying data and improve accuracy. The resulting data is then to be used as reference data for comparison when the actual search operation is performed. In this case, the robot is still to travel along the same pre-planned path through the search area, but when a distance measurement is taken that varies significantly from the reference data obtained in the absence of the destination base's existence, this measurement indicates the existence of the base and also provides information on its location relative to the device. At this point, the robot is to use this information to determine an approximate initial bearing to take to approach the destination base, and will switch over to the basic distance sensing algorithm selected in Section 3.3.4 to target and travel to the base.

3.3.4.2 Extended Arm Deflection Sensing Algorithm

The extended arm touch sensing algorithm involves the concept of physically contacting the base in order to know exactly where the base is. The theory of operation is that a retractable arm driven by a servo motor will start to extend from the robot out into the open space as shown below in Figure 20.

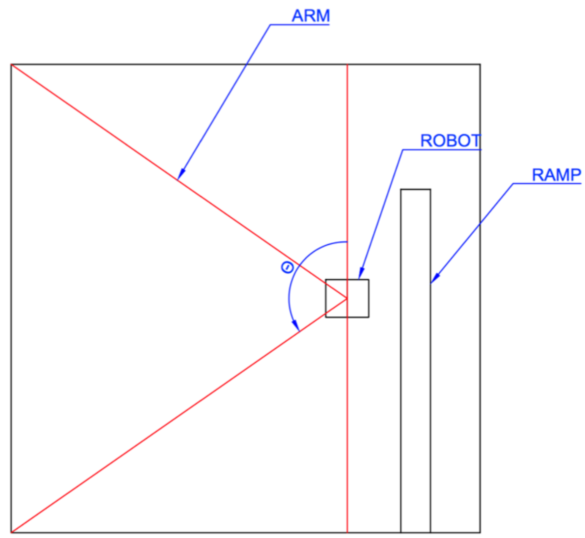


Figure 20: Extended Arm Sensor

This creates an arm for the robot that will search the area in front of the robot through touch, much like a cane for those with visual disabilities. As the robot rotates, the arm will extend to the extents of the search area on the other side of the wall. The extended arm will be a flexible arm that will deflect once it touches the object as the robot continues to rotate. This deflection will be measured by an additional distance sensor, which will allow the robot to know when the base has been detected, and can also be used to compute the direction that must be taken to approach the base.

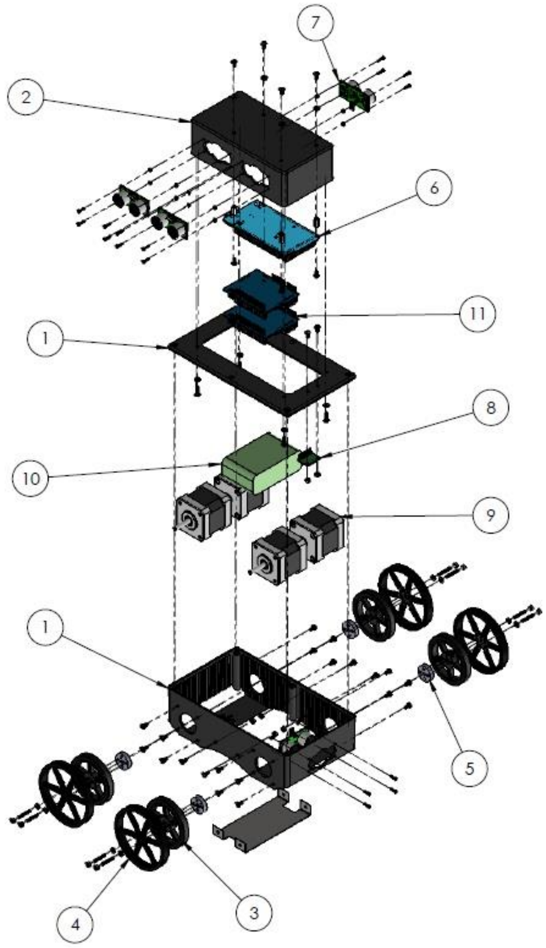
3.3.4.3 Destination Base Detection Algorithm Evaluation

The extended arm deflection sensing algorithm possesses an advantage over the reference distance data comparison algorithm in that it will likely require less time to detect the destination base, although this is under the assumption that there is no limit on both the length of the extension arm and the maximum distance measurement that can be taken. This is based on the necessity to travel around the entire search area in the case of the distance data comparison method, whereas the arm deflection method ideally requires only a single rotation of the robot to locate the base. However, the distance data comparison algorithm also precludes the need for an additional motor, which would be required to extend the arm, as well as the arm itself, which provides the distance data comparison method with a significant advantage in terms of minimizing weight. Furthermore, the addition of the extension arm requires additional mechanical design and complexity in modeling the deflection of the extension arm accurately, which in turn increases uncertainty in the relative location of the destination base. Thus, the reference distance data comparison algorithm is taken as the selected base detection algorithm.

3.4 Testing

The proposed test plan for the designed robot begins by validating each of the basic components of the robot. This includes testing the motors as the robot is moving, the correctness of the IMU measurements, and the distance measurements received from the ultrasonic sensor. Testing the motors include testing the robot travelling on the floor in any direction as well as the robot travelling up and down the ramp. For the IMU, the test required is to validate the sensor's results as the robot in moving up and down the ramp. Lastly, for the ultrasonic sensor, the test required is to determine the minimum hold time for the sensor to obtain an accurate measurement to an object, its precision, as well as its minimum and maximum range. After the basic components of the robot are tested, the ramp and base detection algorithms must be tested. This will involve how the robot detects the ramp and base by differentiating from the surroundings as well as testing the algorithm from different angles of approaches.

3.5 Summary of Final Design



Shown below in

Figure 21 is an exploded view of the final design with the major design parts labeled. For the full assembly drawings refer to Appendix B.

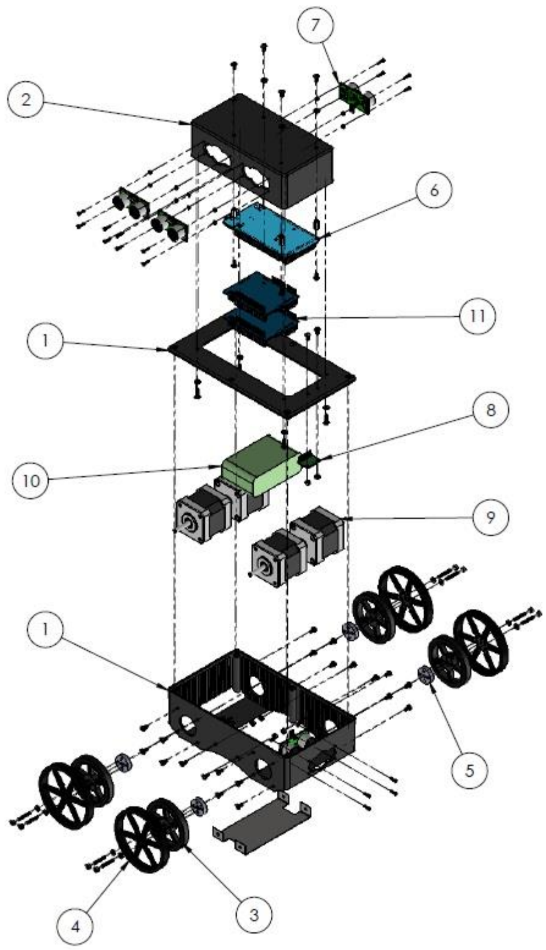


Figure 21: Final Design Exploded View

The bill of materials for the major components is listed in Table 11 below. For the comprehensive Bill of Materials please refer to Appendix B.

Table 11: Major Parts Bill of Materials

Item Number	Part Number	Quantity	Source
1	Hammond 1591 E	1	Sayal
2	Hammond 1591 D	1	Sayal
3	60 mm Pololu Wheel	4	Creatron
4	80 mm Pololu Wheel	4	Creatron
5	Hub	4	Creatron
6	Arduino Mega 2560	1	Adafruit
7	HC-SR04 Ultrasonic	4	Robot Shop
8	6 DOF Gyro, Accelerometer IMU	1	Robot Shop
9	12 V 0.4 A Unipolar Stepper Motor	4	Robot Shop
10	Ni-Mh Battery	1	Robot Shop
11	Motor Shield	2	Adafruit

3.5.1 Expected Performance

Knowing that the maximum range of the selected ultrasonic sensors is 500 cm [9], the path that must be traveled by the robot on the search site side of the mountain range wall is determined, and the distance traveled on that side is determined to be 185.39cm. Assuming that the starting base is located at the furthest edge of the starting side of the mountain range wall and the trajectory of its travel to the ramp will be purely orthogonal or parallel to the ramp and wall, the distance traveled on the starting side is 135.77cm. The complete trajectory is shown in Figure 22 below.

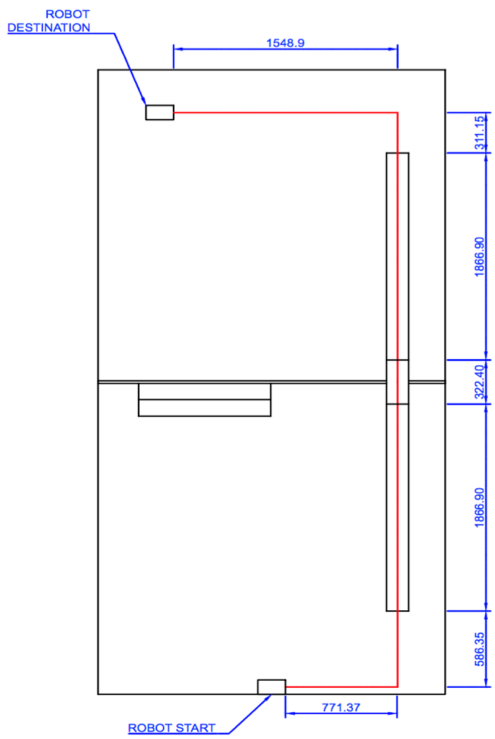


Figure 22: Complete Trajectory of the Robot

The combined ground travel distance is therefore 321.16 cm. Knowing that the operating speed of the stepper motors is 90 rpm [12], and that the robot will always be traveling on the outer 8.0 cm diameter wheels while on the ground, the robot's ground speed will be 2261.95 cm/min or 37.70cm/s. Therefore, the robot's combined ground travel time is 8.50 s.

The robot's ramp travel distance is 186.69 cm per incline in addition to the 32.24 cm segment at the top of the ramp, giving a total ramp travel distance of 405.62 cm. Using the same motor operating speed of 90 rpm and knowing that the robot will be traveling on the inner 6.0 cm diameter wheels while on the ramp, the robot's ramp speed is determined to be 1696.46cm/min or 28.27cm/s. Therefore, the robot's total ramp travel time is 14.35 s, and the overall travel time is 22.85 s.

The battery used will allow for the robot to last 0.49 hours, which is sufficient time to allow the robot to run with the for the estimated travel time as well as allow for multiple rounds of testing without having to recharge.

4 Conclusions and Recommendations

The mechanical design for the final device includes a store-bought enclosure, and staggered inner and outer wheels with 60 mm and 80 mm respective diameters used as a ramp guiding mechanism. The electrical design includes selection of an appropriate stepper motor, the Adafruit motor shield for the Arduino, ultrasonic sensors for distance measurement, an economical inertial measurement unit for ramp sensing and a 12 V power supply. The control system design uses a boundary offset algorithm for distance sensing, a tilt detection algorithm for ramp alignment and a reference distance data algorithm for destination base detection.

Basic commissioning and component verification should be performed next, followed by integration and basic functionality testing. More detailed sensor testing should also be performed for metrics including required hold time and actual sensor range and resolution, particularly for the ultrasonic sensors.

5 References

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Appendix A – Static Coefficient of Friction Verification

An experiment was performed to verify the static coefficient of friction of the rubber wheels on plywood. A block of wood was used to represent the body of the vehicle and the wheels were attached by drilling holes into the wood where the screws on the wheel were inserted. The mass used doesn't matter because the formula for finding static coefficient of friction is $\mu_s=\tan\theta$, and only depends on the angle where slipping occurs. A piece of plywood was used to represent the ramp and a phone was taped to the plywood with an app that would tell us the angle that the wood was at. The setup can be seen in Figure 23.

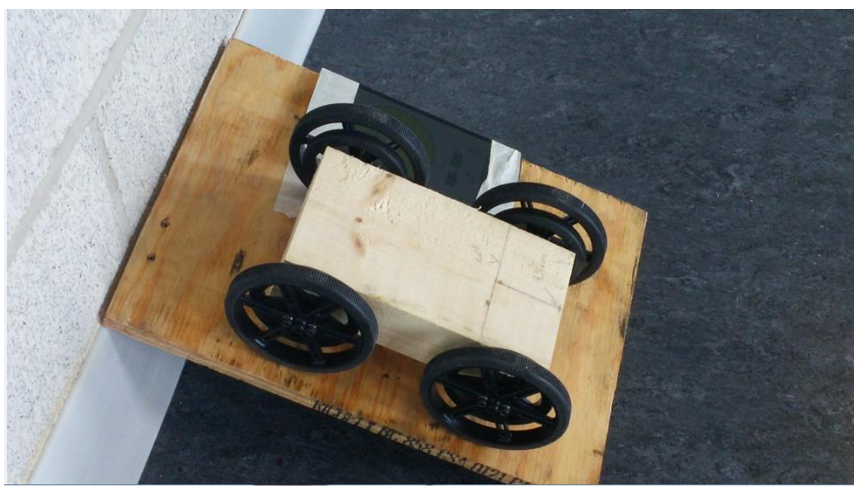


Figure 23: Test setup for finding the coefficient of static friction

The experiment was done by placing the model vehicle on different locations on the plywood each time and raising the plywood until the vehicle started to move, and recording the angle this occurred at. This was repeated 10 times and on average it was found that the vehicle slipped at an angle of 41.3°, which corresponds to a static coefficient of friction of $\mu_s=0.878$, using $\mu_s=\tan\theta$.

Appendix B – CAD Drawings

Figure 24 to Figure 27 below outline all the mechanical CAD Drawings for the enclosure that holds all the parts for the final robot together.

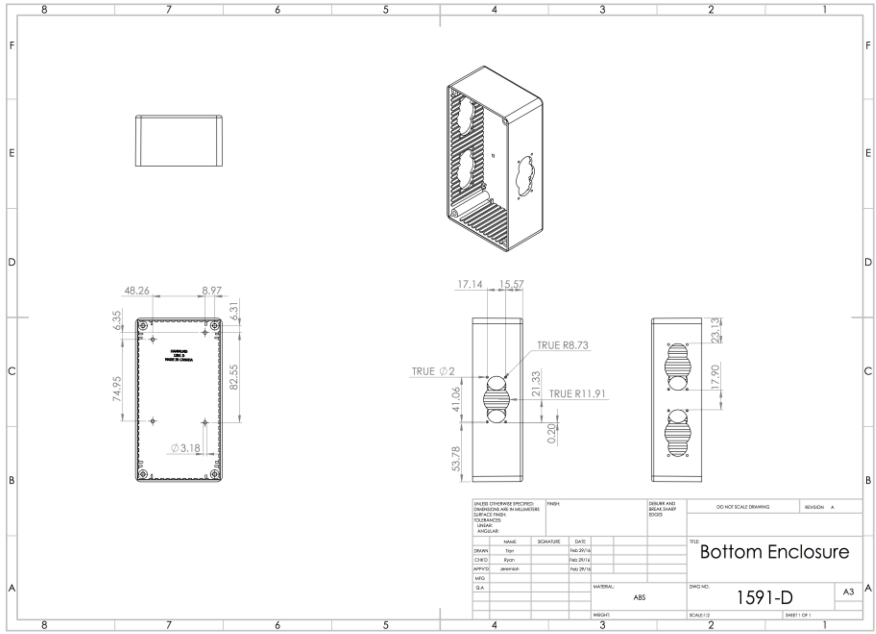


Figure 24: Bottom Enclosure

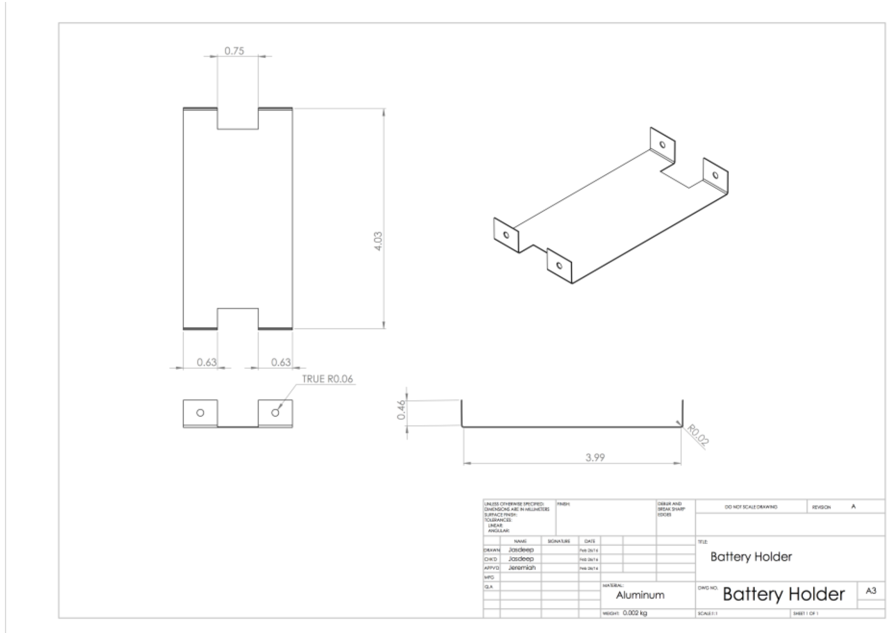


Figure 25: Battery Holder

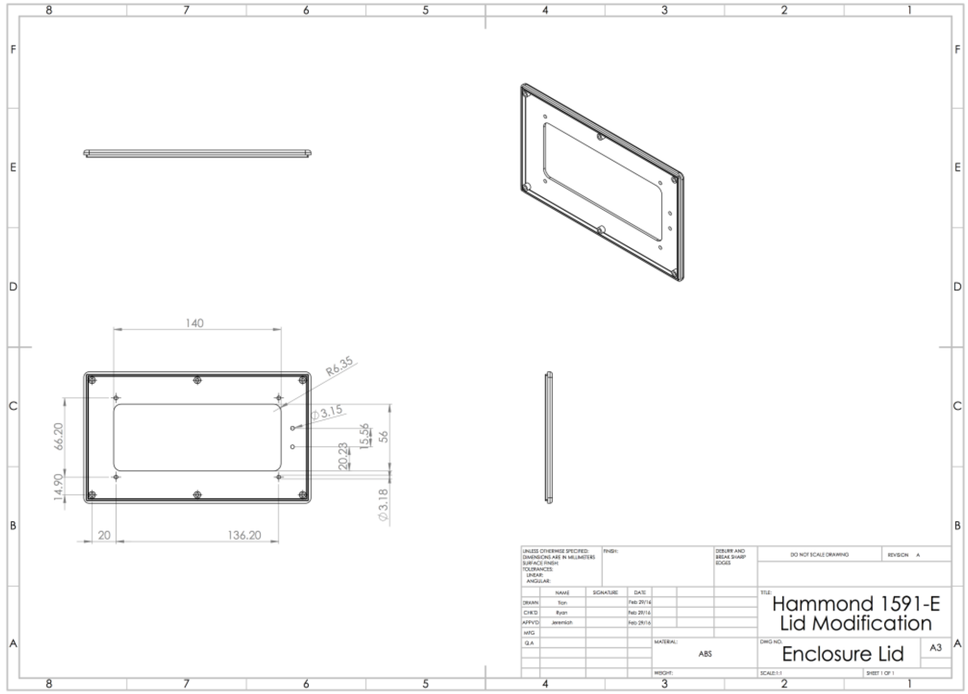


Figure 26: Enclosure Lid

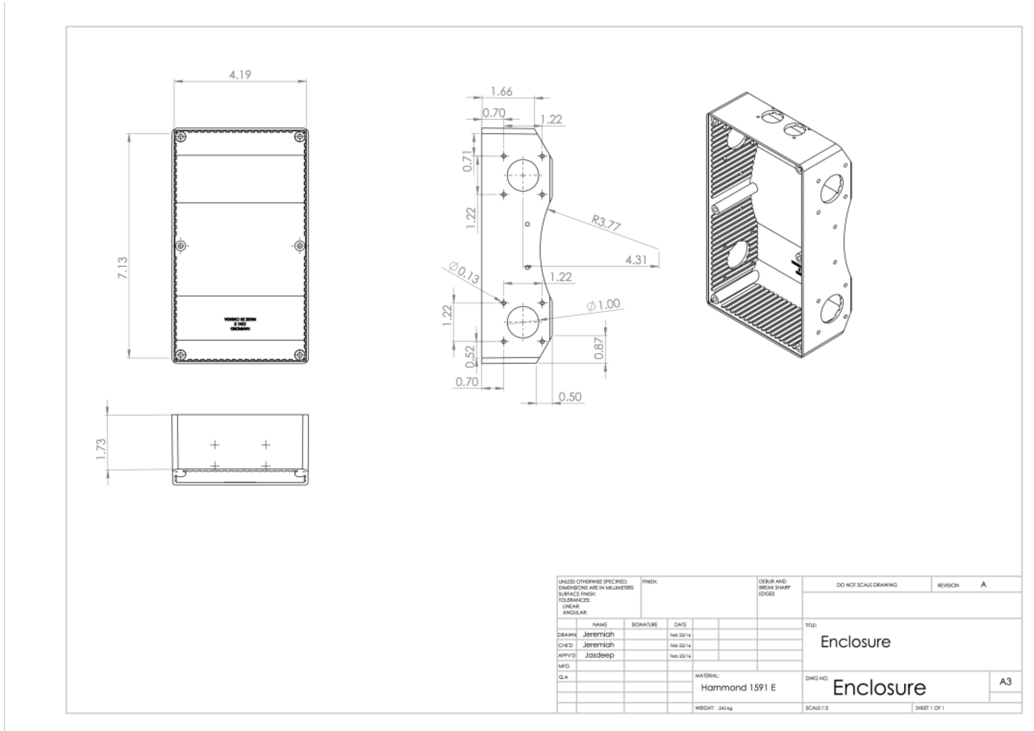
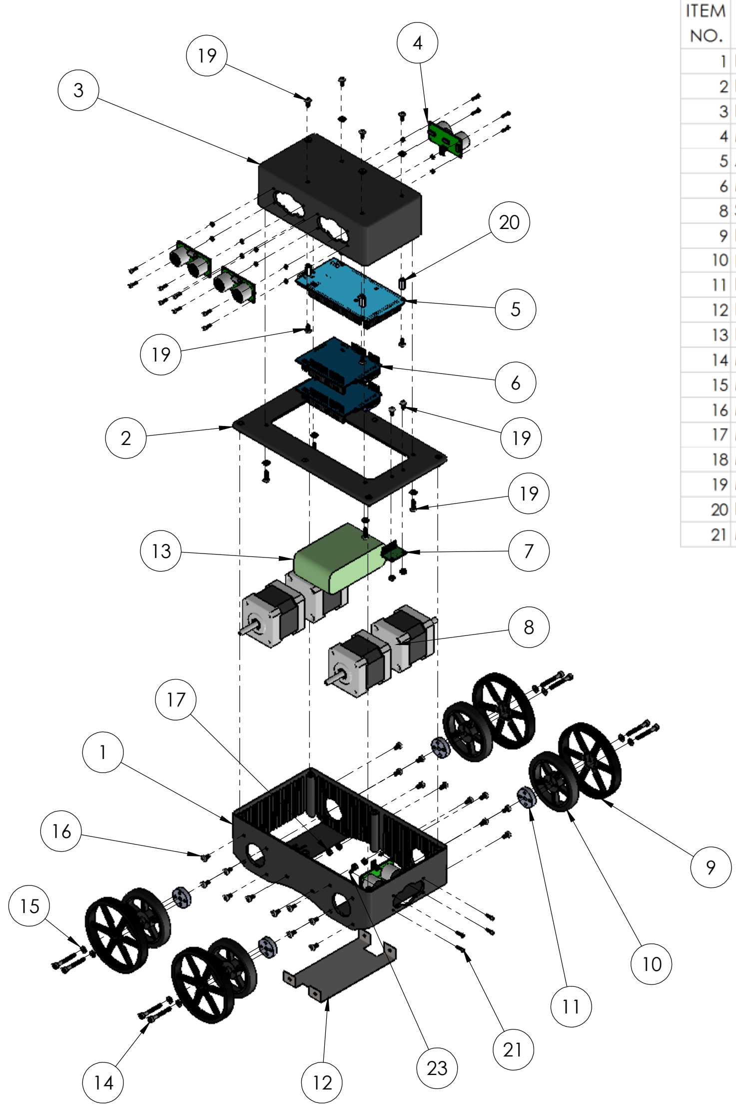


Figure 27: Enclosure



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Hammond 1591-E	7.5" x 4.3" Enclosure Bottom, Black, Modified	1
2	Hammond 1591-E	7.5" x 4.3" Enclosure Lid, Black, Modified	1
3	Hammond 1591-D	5.9" x 3.2" Enclosure Bottom, Black, Modified	1
4	MPU 6050 IMU	6 DOF Gyro, Accelerometer	1
5	Arduino Mega 2560	Arduino Mega 2560	1
6	Motor Shield V2.3	Adafruit Motor Shield	2
8	Soyo SY42STH38-0406A	12 V, 0.4 A, Unipolar Stepper Motor	4
9	Pololu 80mm Wheel	80mm diameter wheel, rubber tires	4
10	Pololu 60mm Wheel	60mm diameter wheel, rubber tires	4
11	Pololu Shaft Hub	Hub for 5mm shaft diameter	4
12	Battery Holder	Battery Holder (custom)	1
13	Robotshop RB-Sta-12	12V 1600mAh NiMh Battery	1
14	McMaster-Carr 91290A125	M3x25mm Socket-Head Screw	8
15	McMaster-Carr 93475A210	3mm Flat Washer	16
16	McMaster-Carr 90116A151	M3x6mm Pan-Head Screw	30
17	McMaster-Carr 92497A200	M3 Hex Nut	6
18	McMaster-Carr 90591A265	M2 Hex Nut	16
19	McMaster-Carr 90116A155	M3x10mm Pan-Head Screw	4
20	Keystone 24423	M2x10mm F/F Spacer, Hex	4
21	McMaster-Carr 90116A015	M2x8mm Pan-Head Screw	16

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	NAME	SIGNATURE	DATE		TITLE: Downfall Assembly Drawing	
DRAWN	Jeremiah		02/29/16			
CHK'D	Anthony		02/29/16			
APPV'D	Jasdeep		02/29/16			
MFG						
Q.A				MATERIAL:	DWG NO. Downfall	A3
				WEIGHT:	SCALE: NOT TO SCALE	SHEET 1 OF 1