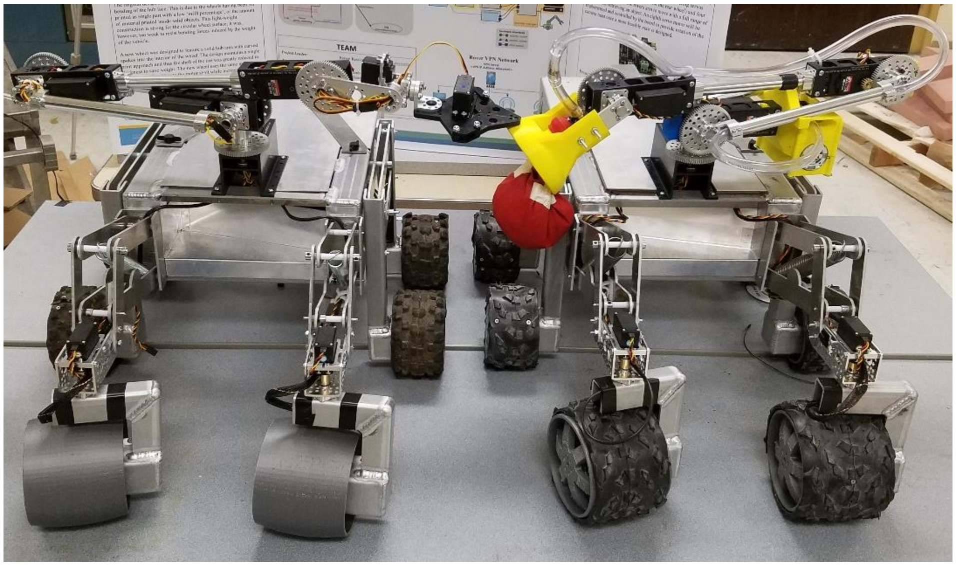
National Institute of Aerospace
RASC-AL Robo-Ops 2016

University of Wyoming

Cowboy Robotics
Technical Report



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Introduction

The Cowboy Robotics team at the University of Wyoming is proud and excited to compete in the 2016 RASC-AL Robo-Ops competition. The team has high hopes that the two rovers, Steamboat and Pistol Pete, offer distinct advantages that will provide unique performance in the Johnson Space Center rock yard.

System Description

Our two semi-identical rovers feature a unique shrimp suspension and drive system. This type of suspension is passive, requiring no control or power, as it's designed around the basic mechanical elements of four-bar mechanisms assisted by springs. With the articulating elements in pairs and a single fixed rear wheel, the rovers are driven by seven gear-reduced DC motors, housed inside the wheels and protected by aluminum motor housings. The two main advantages of this system are its ability to adapt to the changing terrain while leaving the top of the rover free to mount a robotic arm.

Both rovers feature a four degree of freedom arm, mounted along the longitudinal axis of the rover. These arms are capable of rotating 360 degrees at the base and can reach the ground approximately 270 degrees around the rover. Collected samples will be deposited into a collection bay directly between the front suspension arms.

Overall Competition Strategy

Our strategy revolves around the age-old concept of divide and conquer. Our 2 rovers will be able to cover vastly more territory and their differing grippers will allow us to quickly acquire samples from a variety of terrains.

Technical Specifications

- Speed

The rovers at full speed on level ground clocked in at 0.56 m/s, or 1.25 mph.

- Weight

Each rover currently has a mass of 15.40 kg, for a grand total of 30.80 kg.

- Size

Both rovers are 88 cm long and 50 cm wide, with a stowed height of 49.5 cm and a deployed height of 77.5 cm.

- Obstacles & Payload

Each rover has been documented driving through a variety of inclines and over obstacles 15 cm tall with a payload volume of 0.5 ft^3 and enough torque to carry any amount of rocks that can fit therein.

Testing will continue up until the competition itself, but so far each rover has been tested in sand, on gravel, in grass, on inclines, and going over obstacles, in addition to sample collection testing.

- Operating time

Measurements of the power draw of the system

- Drive power

A maximum drive power of 420 W is possible with our seven 12V DC motors.

- Battery:

To supply power, a Tenergy 12.8V, 20Ah, LiFePO4 chemistry battery pack was selected. This battery offers good performance in demanding conditions, limited heat emission, high current draw capabilities, a stable chemistry, and good resistance to damage in case of impacts.

- On-board Computer System and Hardware:

The core of the on-board computing system is the Supermicro A1SRI-2558F, a mini-ITX motherboard with a built in quad-core Intel Atom C2558 System on Chip (SoC). This motherboard was selected due to it providing a total of four USB 3.0 ports and two USB 2.0 ports. A Samsung 850 EVO 250 GB SATA III Solid State Drive with up to 540 MB/s read and 520 MB/s write speed is used. Additionally, two sticks of Kingston Technology 8 GB 1600 MHz DDR3L RAM are installed on the motherboard. Since nearly all computation and processing will be done on the motherboard, these components were selected for their speed and reliability. To control the motors and servos, an ATmega328P chip is connected to an Adafruit 16-Channel 12-bit PWM/Servo breakout board with I^2C interface. The breakout board's PWM output pins are connected to Pololu Simple single channel and Robo Claw dual channel motor controllers. A diagram of the system is shown in Figure 1.

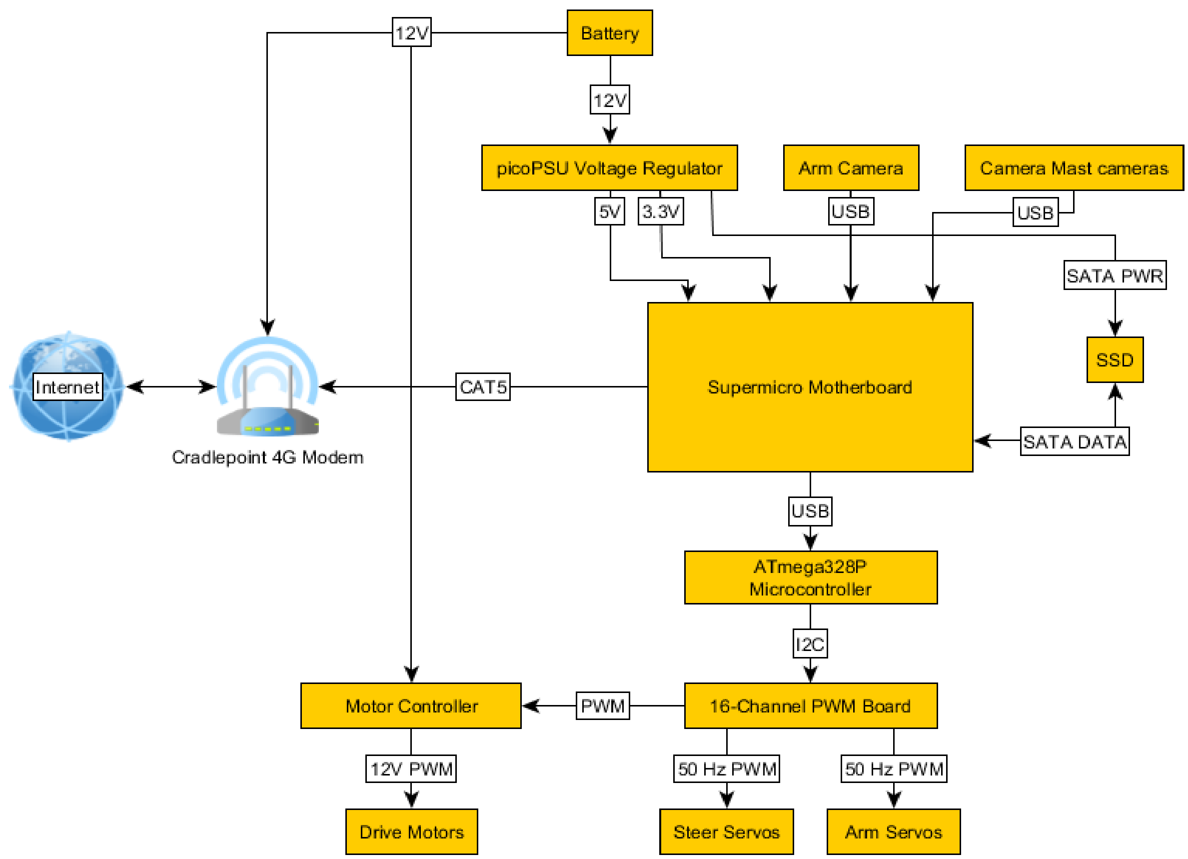


Figure 1: On-board electronics

- Software Framework

The rovers are controlled by the Robot Operating System (ROS), a communication framework for distributed robotics programs. ROS allows the rapid implementation of prewritten and custom programs, called “nodes”; there are over 2000 pre-existing nodes available for download and libraries available to write code for nodes developed by the team. ROS nodes are able to communicate with other nodes and to external applications through communicational channels called “topics.” Messages through ROS topics can range from formatted text to images. ROS nodes in each rovers’ software framework will handle everything from actuating the servos and motors to processing the image data and creating a 3-D map of the environment.

Mechanical Systems

Chassis

The two rovers, Steamboat and Pistol Pete, were designed and built to be nearly identical with the exception of the sample acquisition strategy. The chassis, suspension, and body panels of the rovers are made of 5052 Aluminum, selected for its bendability at the expense of some material strength, is lightweight, sufficiently sturdy, and has favorable thermal properties for improved heat dissipation. A Finite Element Analysis (FEA) model of the chassis itself was created and analyzed in Abaqus to determine the maximum loading the chassis could sustain before failure. As a worst-case loading scenario, the entire weight of the rover multiplied by a factor of safety of four and applied to the rear wheel mount of the frame. The maximum resultant stress was 13,533 psi, just slightly above the 13,000 psi yield stress of aluminum 5052. The simulation results, shown in Figure 2, infer that with the addition of the aluminum box to the chassis, the rover can withstand an impact four times the force of its own weight concentrated at the rear wheel mount, the aspect of the chassis most susceptible to failure. As a worst-case loading scenario, the entire weight of the rover multiplied by a factor of safety of four and applied to the rear wheel mount of the frame.

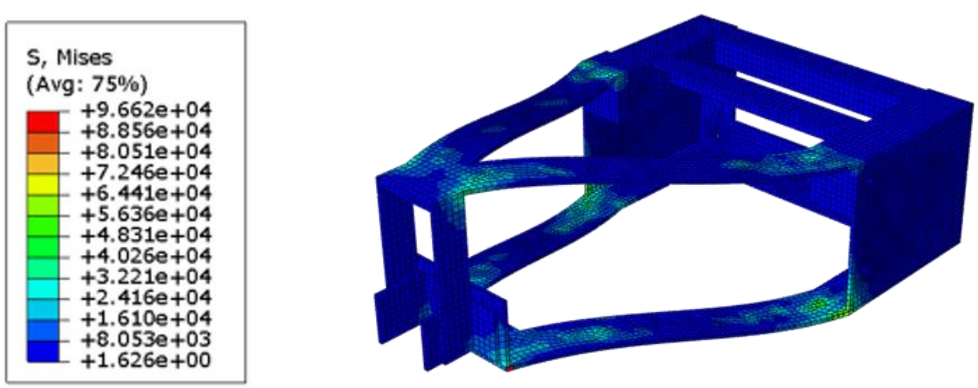


Figure 2: Von Mises stresses on the rover’s chassis under critical loading

The chassis itself was entirely re-designed over the course of the past year. Notable improvements include full enclosure of each rover’s internals while simultaneously reducing the chassis weight by half, as well as providing more interior room and quick, tool-less access to the interior. The new assembly is shown in Figure 3.

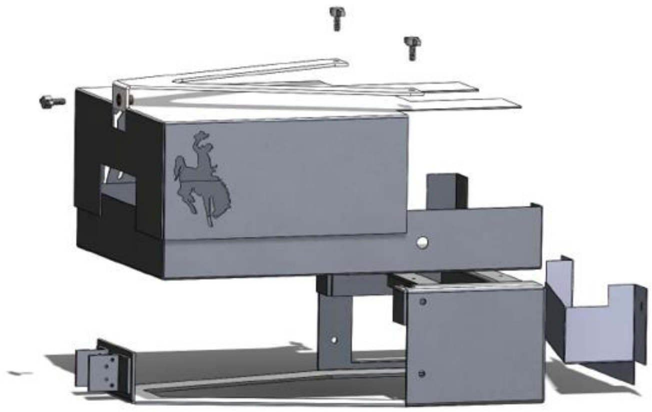


Figure 3: Re-designed chassis and body

Suspension

The shrimp suspension system utilized by both rovers consists of two spring-loaded drag-link four-bar suspension elements on front, freely articulating parallel-link four-bar suspension elements on the sides, and a fixed rear wheel on the back to provide stability while driving. A statics model of the front four-bars and of the suspension as a whole is included in Appendix A. The springs for the front four-bars were sized such that on a level surface the front wheels provide a downforce of 29 N – enough force to provide sufficient traction while still allowing the front wheels to extend upwardly upon encountering an obstacle. At full retraction (7.2 cm above horizontal), the front wheel down-force is 59 N, providing twice the lifting force while simultaneously allowing the center wheels to maintain traction with the ground for as long as possible. The front wheels can also travel 15.7 cm down from horizontal to meet the ground upon coming down from an obstacle, at which point the springs provide slightly more than their 4.5 N pre-load. The shrimp suspension system was chosen in order to provide each of the two relatively small rovers with maximum versatility over rough terrain. With this suspension configuration, each rover has been documented driving through a variety of inclines and over obstacles 15 cm tall with a payload volume of 0.5 ft^3 and enough torque to carry any amount of rocks that can fit therein.

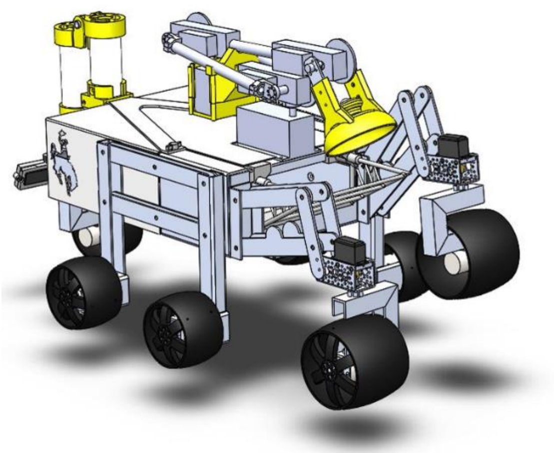


Figure 4: Shrimp suspension

Drive System

Seven powered wheels, mounted as shown in Figure 4, provide motion for the rover. Steering is achieved through a combination of 3 mechanism: steering servos on the front two and rear wheels, modulation of the power applied to the differently sized wheels to maintain a uniform speed, and modulation of the power to each motor channel based on the turning radius. This allows nimble and smooth control of the rover, and even provides the ability to turn within itself in a differential manner.

A custom, 5-channel motor-controller was designed and a printed circuit board (PCB) fabricated in order to achieve individual control over all seven DC motors. Throughout testing however, it was found that the microcontroller onboard the PCB tended to reset at random when the motors were at full speed. Unfortunately, the issue remains unresolved due to time constraints to appropriately prepare for the competition. Instead, it was decided that commercially available motor controllers would be used for the rovers drive systems. On board each rover, there are two two-channel Pololu motor controllers and one one-channel, which are used to drive the seven DC motors on five channels. These motor controllers allow bi-directional speed control over each DC motor while also allowing an adjustable maximum acceleration and deceleration to limit the amount of mechanical and electrical stress on the system. The motor controllers signal is produced by 5 channels from a dedicated PWM servo control board, which interfaces with an ATMega328P microcontroller.

Motors with a built-in gear reduction of 100:1 were selected for torque rather than speed. The gear-reduced, unloaded motors spin at 100 RPM, and at about 96 RPM when loaded. Each motor is located within the wheel itself, inside a protective suspension housing that went through several design iterations before reaching the current design (see Appendix C).

Each of the newly-designed wheels is mounted directly to the motor shafts by an aluminum hub. After the original rover wheels failed in bending at the hubs due to sparse infill in the 3D printed wheels, new wheels were manufactured. The new wheels, while also 3D printed, feature a number of improvements: they were printed solid, to provide the necessary rigidity, they feature inwardly curved spokes to spread the bending stress and reduce weight, and a barrel-shaped drive-surface geometry to improve surface contact on uneven terrain, thus providing better traction. An FEA model was developed which determined the theoretical load limit for an individual wheel to be 240 N, roughly the force applied by a 23.6 kg load. The stress distribution on the wheel during loading can be seen in Figure 5.

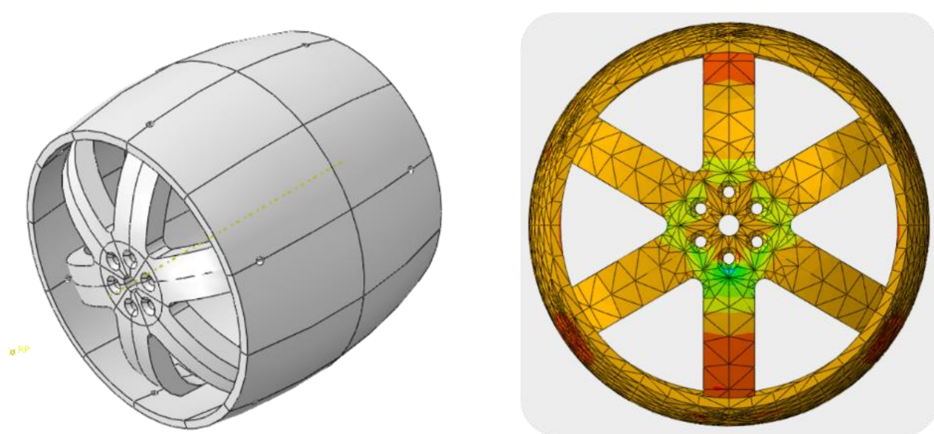


Figure 5: New wheel design (left) and corresponding stress distribution (right)

Each wheel is wrapped in mountain bike tire tread to maximize stability and grip on a multitude of terrains. The tread patterns used can be seen in Figure 6.

Figure 6: Tread patterns of the two rovers

Sample Acquisition

Manipulator System

The manipulator is the only aspect in which the rovers are not identical. One rover, Steamboat, is equipped with a granular gripper. The other rover, Pistol Pete, uses a more traditional claw-style gripper. Each rover features the same arm, an off-the-shelf four-degree-of-freedom arm kit from Servo City. The claw gripper adds two additional degrees of freedom, however, with wrist rotation about the forearm axis and a degree of freedom to open and close the claw; however, there are only two points of contact between the claw and the specimens, making objects trickier to pick up. To compensate for this, the arm has been made analogous to a human arm, with five total degrees of freedom in addition to opening and closing of the claw. Each degree of freedom operates in a single plane, with the following ranges of motion:

1) First servo (shoulder rotation about base): full rotation parallel with rover chassis
2) Second servo (shoulder extension): 180° – 250° (between cradle and point of contact with chassis)
3) Third servo (elbow extension): 360°
4) Fourth servo (wrist extension): 190°
5) Fifth servo (wrist rotation. specific to the claw gripper): 360° about the forearm axis
6) Sixth servo (claw manipulation): fully opens and closes claw (servo rotation of 90°; claw opening is 2.8in wide when fully open)

The arm has an extended radius of 60 cm. The granular gripper makes full use of this, with a collection radius of 60 cm from the center of the arm's base. The claw gripper, with addition length due to the rotating wrist, has a collection radius of 80 cm. Both rovers have a camera directed at the gripper for sample acquisition.

Gripper

A granular gripper was selected for Steamboat because of the wide variety of objects which can be picked up without losing time to tedious claw-gripper alignment. The small DC vacuum pump for the granular gripper can be seen in Figure 7, as well as the cradle for the arm. The arm and gripper assembly on Pistol Pete is the same minus the 3D-printed pump housing and of course with a claw gripper instead of the granular gripper. Deciding on a claw manipulator for one of the rovers was not only to amplify the possible collection scenarios, but more importantly was for collection redundancy should the granular gripper experience difficulties. Testing has shown that the granular gripper excels in picking up objects with a variety of sizes, shapes and weights, but struggles in picking up objects nestled among other things. Testing of the granular gripper will continue during the next two weeks, though a second claw gripper has been purchased and assembled as a contingency plan.

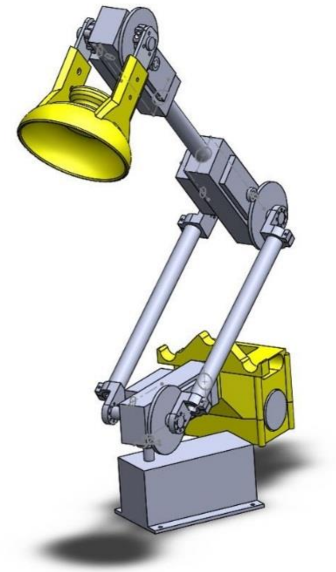


Figure 7: Arm with granular gripper

Sample Acquisition Strategy

To most effectively take advantage of having two rovers, Steamboat will be sent to the part of the course that has the most samples out in the open, whereas Pistol Pete will go after the samples that Steamboat would have more difficulty with. On both rovers the pre-programmed home position for the arm will be in the cradle with the servos powered down, with the gripper resting directly over the collection bucket. This pre-programmed home position not only saves power between sample collections, but also allow for one-touch arm and sample storage once the gripper has secured a sample.

Software and control

Software Framework

The rovers are controlled by the Robot Operating System (ROS), a communication framework for distributed robotics programs. ROS allows the rapid implementation of prewritten and custom programs, called "nodes"; there are over 2000 pre-existing nodes available for download and libraries available to write code for nodes developed by the team. ROS nodes are able to communicate with other nodes and to external applications through communicational channels called "topics." Messages through ROS topics can range from formatted text to images. ROS nodes in the rover software framework will handle everything from actuating the servos and motors to processing the image data and creating a 3-D map of the environment.

Networking and Connection

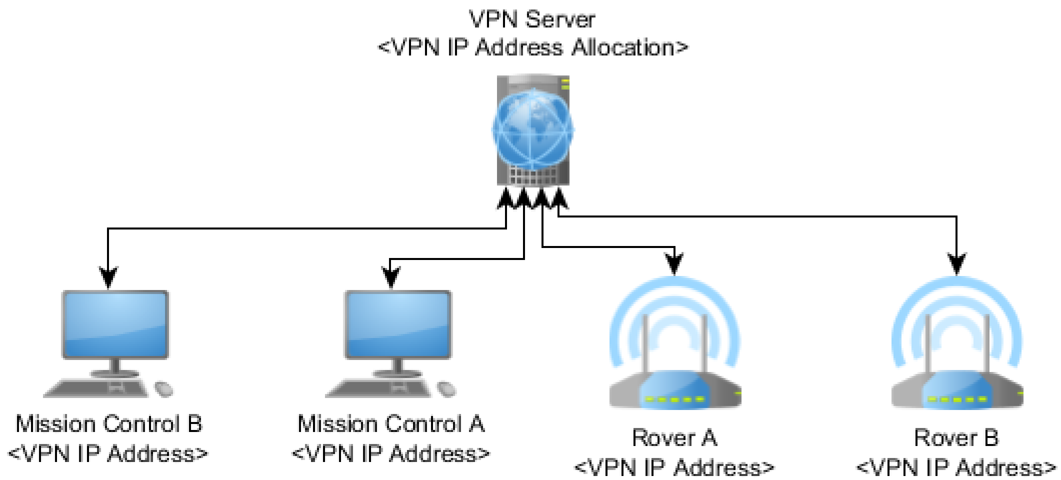


Figure 8: VPN network set up

For secure, remote communications over the internet, a Virtual Private Network (VPN) was set up on a commercial data center, which provides reliable up time and fast network speeds. The VPN is used to generate a static IP address for each rover, and to provide a secure intermediary connection between the rovers and mission control. Onboard each rover is a CradlePoint IBR650 4G Modem which provides internet access through an unlimited and un-throttled data plan provided by Verizon Wireless. In addition, this data connection provides a unique static IP address for each rover, which will serve as a contingency plan in the eventuality of a VPN network failure. This allows mission control to regain control over the rovers through Secure Shell (SSH) access to the Verizon Wireless static IP addresses. Through this network set up, the download speed tested at 15 Mbps and the upload speed at 5 Mbps. When issuing a ping from mission control to the rover, a 210 millisecond latency was observed. When the rover is live streaming the camera feeds to mission control, a one to two second delay was observed in the stream when holding a timer to the camera.

Arm and Drive Control System

The arm and drive control systems are comprised of 5 ROS nodes in total, 3 of which are shared between the two systems. These 3 common nodes are the command receiver node running on an ATMega328p microcontroller chip onboard each rover, the command parser node whose role is to receive and parse user input at mission control, and the translator node which serves as the interface between the parser and receiver nodes and also runs at mission control. There are two supplementary nodes which serve to read user input from physical devices and relay this input to the aforementioned command parser node: the ROS keyboard, and the ROS joy node.

The next node in the chain (the command parser node) is responsible for intercepting and parsing input from the keyboard and joy nodes. This node was written in order to keep track of the current servo angles and motor speeds for each rover, and calculate new angles and speeds from the input it receives. Once input has been parsed and the new rover settings have been calculated, this new data is sent over a rostopic to the command translator node.

The command translator node is responsible for generating PWM values for the angles and speeds it receives. The calculations performed in this node required many hours of calibration – adjusting values in code in order to correctly transform angles and speeds into raw PWM data. Each different servo and motor model type required its own calibration, and gear ratios and wheel diameters were required from the mechanical engineering team in order to correctly approximate these values.

The final node in the system is the command receiver node, running on the microcontroller chip onboard each rover. This chip accomplishes the simple task of generating (with the help of the I2C PWM breakout board) a physical PWM signal, replicating the PWM data received from the command translation node. This signal is then sent to the servo motors and motor controller boards, driving the rover and operating the arm.

The team encountered issues with the limited RAM and computational power of the ATMega238p microcontrollers. While the onboard microcontroller was originally responsible for translating angles to PWM data, this produced dangerous and unpredictable stack overflow errors. It quickly became obvious that optimization alone would not resolve this issue, and that the only solution was to either purchase more powerful hardware, or to lighten the calculation load on the ATMega238p chip. The team opted to use the cost effective solution, which was to delegate the job of command translation to a command translation node.

Camera System

Providing vision for each rover are a pair of Genius 120 degree wide-angle cameras installed on a deployable camera mast. The mast will deploy at competition start by a spring and magnet to a height of approximately 75 cm from the ground. The camera pair is mounted on a slip ring and can thus be panned continuously by a continuous-rotation servo housed in the mast.

The wide view of these cameras allowed us to forgo any pitch mechanism, as the rover chassis up to and beyond the horizon are visible at a pitch angle of 15 degrees. Furthermore, the wide field of view and narrow aperture of these webcams provide a depth of field from the rover chassis out to infinity.

Not only will these webcams provide a live stream to our drivers, they will also be used in tandem to compute a real-time point cloud visualization based on the stereo-vision algorithms available in OpenCV. This point cloud will be sent into rviz, a ROS package, to provide an interactive 3-D representation of the current environment on the rock-yard to the drivers. Additionally, this data can be used to match objects and build an evolving and persistent map of the rockyard to provide pathing assistance, as shown in Figure 9.

Finally, a narrower camera resides on the robotic arm, aimed directly down its length at the gripper, which will provide a direct view of the gripper and the sample to be acquired.

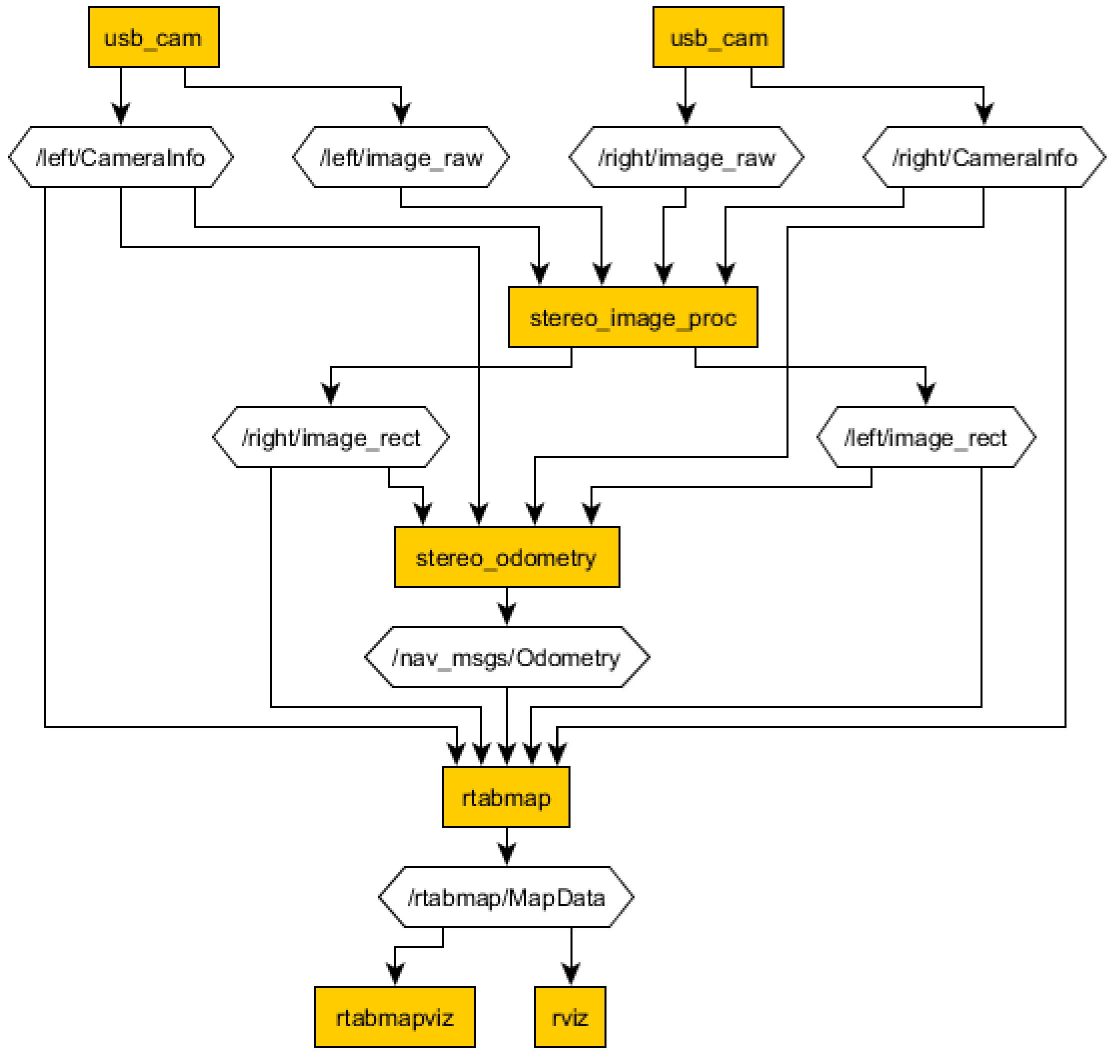


Figure 9: Video streaming and analysis flow chart

Audio

Audio streaming is provided in a similar manner to the camera streaming. A ROS node processes the audio feed through microphones that are embedded into the wide-angle cameras. The audio feed is then streamed through mission control to the public.

Testing Strategy

Laramie is surrounded by a plethora of different terrains that pose challenges to the rovers. In addition to extensive testing of the rovers, and their various systems and components in and around the lab, it was not difficult to find sand, rocks, and hills with which to test the rovers as a whole. Testing will continue up until the competition itself, but so far each rover has been tested in sand, on gravel, in grass, on inclines, and going over obstacles, in addition to sample collection testing. Of particular interest has been testing different attachment orientations for Pistol Pete's claw collector, and thus far, facing forward and parallel with the ground has proven to be the most convenient home location. Test results show that each rover can traverse all environments with relative ease with only minor slipping of the wheels. Going over grass and loose gravel showed the best results with almost no slipping while also obtaining maximum speed. Testing each rover on sand was also a success. The wheels struggled only a little to grab traction while traveling forward as well as when making wide turns. Beginning from a stationary position each rover was unable to perform a sharp 360 turn due to a lack of traction under the steering wheels. While testing large obstacles it was discovered that positioning the front wheels directly in front of an obstacle then slowing applying power to the wheels was the best method for navigating over large objects. Finally, testing each rover on steep inclines showed that as long as the wheels can maintain traction each rover maintains the power necessary to climb the minimum required height and greater. Unlike navigating large obstacles, however, maintaining speed before starting to traverse an incline proved advantageous to maintaining traction, and thus, increasing each rover's ability to climb steep inclines.

With the suspension and integrity of the chassis tested, the main focus of future tests will be on the team's drivers ability to properly navigate all expected terrains and large obstacles, as well as team's ability to handle technical difficulties. Placing both rovers in an unfamiliar location will test the drivers' abilities to plan and execute the best route over difficult terrain. Moving the rovers further away from mission control and forcing expected technical problems such as loss of network connection, unexpected reboots of the system, and loosing vision through cameras will test the team's ability to handle unexpected situations while also providing opportunities to create new contingency plans. Lastly, hiding rock samples in difficult to find areas as well as positioning samples in difficult to obtain positions will test the abilities of the manipulator system and the team's ability to acquire samples quickly and effectively.

This new design was tested via a simple procedure. First, the wheel was supported by the hub and the wheel surface and loaded statically from above only to simulate the rover simply sitting still. Second, the wheel was placed on the ground, also supported at the hub, and an object with known mass dropped from a known height to simulate an impact loading while driving. Upon failure, the wheel did not fail in a brittle manner, but rather fractured extensively along the interfaces of the printed layers, as shown in Figure 10. The tire is attached to the wheel surface in numerous locations, meaning that even if the wheel surface becomes damaged, the tire will prevent the wheel from becoming inoperable, and the spokes will remain intact until significantly more damage is incurred.

Figure 10: Tested Wheel displaying cracks along the layers of the 3D Printed model.

Mission Control operation

Drivers

We will have two drivers, one operating each rover. Each driver will primarily be responsible for the continued operation of their rover, and will operate mostly independently of each other. Data will be shared between rovers automatically through ROS.

The drivers have two physical control devices available to them: a keyboard and a wired Xbox 360 game controller. The keyboard is used for driving (through the ROS *keyboard* package), while the controller is used for arm control (through the ROS *joy* node). This control scheme was chosen in order to separate the two tasks, and to avoid confusion or errors while performing delicate and precise tasks with the arm. Both of the packages used for input collection are open source and available on the ROS website.

Interaction mechanism

The drivers will interact with the rovers through a ROS package called rviz. Rviz can render a 3D view of the world surrounding the rover that will be filled in by the data collected through the stereo cameras. It allows the user to specify a location and direction and have the rover control system figure out the best way to get there, much like a top-down click-to-move video game.

Democratic decision making

Decisions for rover operation during competition will be made as a semi-democratic process primarily between the drivers and director, with input from the remainder of the Mission Control team. The Director will manage both drivers and help direct them with aid from the generated 3D map. He will monitor the number of samples collected and their locations and have the authority to direct one rover to assist the other and call a Mulligan, should it become necessary. Also giving the director information will be another member of the team whos sole job is to monitor our connection with the rover and the entire network path inbetween. Further, we will have a member of the team monitoring onboard hardware ensuring all pieces are functioning within optimal parameters and battery life will be sufficient to complete each rover's mission.

Contingency Plans

Through rigerous testing and a firm understanding of all onboard equipment several contigency plans will be written out, step by step, that will walk any member of a team through a known solution to all forseen anomolies. These contigency plans will be well practiced before competition through test runs specifically designed to test and develop these procedures. Finally a specific point will be designated for each rover at which a castastrophic failure is assumed and the second rover will be sent, if possible, to retrieve any payload the failed rover was carrying.

Practicing

Throughout the year, we have scheduled several "dry-runs" to practice mission control and rover operation. However, we have been unfortunately plagued by motor controller issues, which has delayed our testing until recently. With operational rovers, practice has become a daily routine, including training our competition participants (Away Team) on rapid assembly and dissasembly of the rovers.

Budget

Cowboy Robotics has been able to participate in the 2016 RASC-AL Robo-Ops competition thanks to the generous support from NASA, from the National Institute of Aerospace (NIA), from the Wyoming NASA Space Grant Consortium, and thanks to the University of Wyoming for the use of all the facilities that enabled the design, construction and testing of the two rovers. The initially proposed budget and corresponding money spent throughout the year may be seen in Figure 11.

Total Budget	Planned Remaining budget	Actual Spent	Actual Remaining	% Remaining Overhead
$ 12,250	$ 300	$ 9,501	$ 2,749	22%
Travel	$ 5,000	$ 2,886	$ 2,114	42%
Arm	$ 650	$ 681.13	$ (31.13)	-5%
Batteries	$ 700	$ 679.19	$ 20.81	3%
Body Panels	$ 200	$ 70.49	$ 129.51	65%
Bucket	$ 200	$ -	$ 200.00	100%
Cameras	$ 300	$ 199.92	$ 100.08	33%
Camera Mast	$ 300	$ 150.95	$ 149.05	50%
Chassis	$ 300	$ 211.88	$ 88.12	29%
Coms	$ 1,200	$ 1,815.91	$ (615.91)	-51%
Gripper	$ 200	$ 65.94	$ 134.06	67%
Hardware	$ 2,200	$ 2,115.46	$ 84.54	4%
Suspension	$ 550	$ 537.98	$ 12.02	2%
Wheels	$ 150	$ 85.76	$ 64.24	43%

Figure 11: Budget allocation

Public Engagement

Many efforts were made to engage the general public in Cowboy Robotics' participation in this competition. Throughout the course of the year, project updates and advancements were posted to the Cowboy Robotics website and Facebook page. Additionally, several public presentations were given regarding the rovers and the design work and testing that went into them, and tours were given to potential incoming engineering freshmen as a part of showcasing the robotics projects and design work in progress at the University of Wyoming. Community members were invited to rover testing performed in a local park, and the Cowboy Robotics team also partnered with the Laramie Robotics Club to engage the younger generation in robotics.

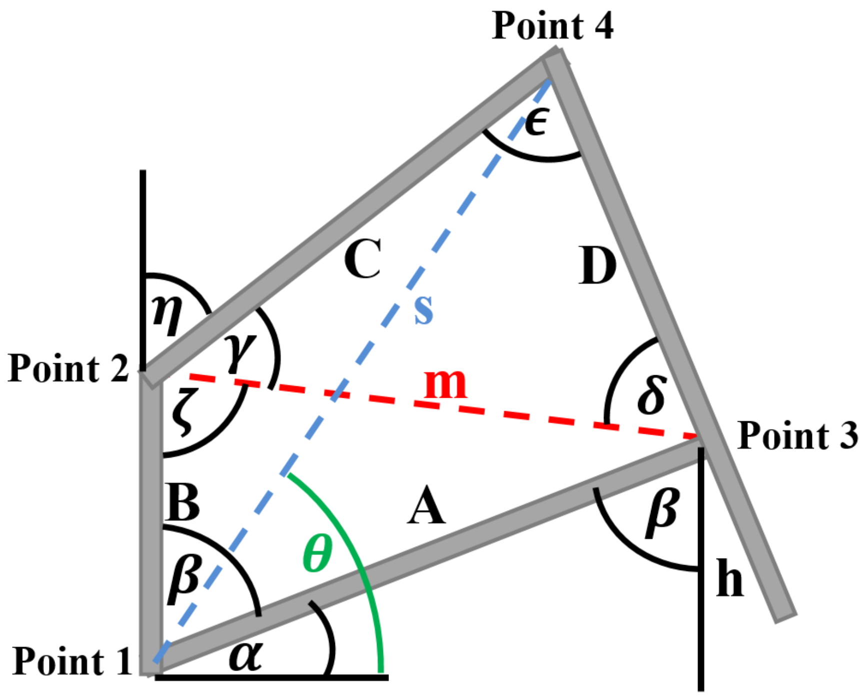
Appendix A: Statics Calculations for the Rover Suspension

Front Suspension Element:

$h = user\ defined$

Angles:

- $\alpha = sin^{-1}\left(\frac{h}{A}\right)$
- $\beta = 90° - \alpha$
- $\gamma = cos^{-1}\left(\frac{C^2+m^2-D^2}{2Cm}\right)$ (law of cosines)
- $\delta = sin^{-1}\left(\frac{C}{D}sin(\gamma)\right)$ (law of sines)
- $\epsilon = 180° - \gamma - \delta$
- $\zeta = cos^{-1}\left(\frac{B^2+m^2-A^2}{2Bm}\right)$ (law of cosines)
- $\eta = 180° - \gamma - \zeta$
- $\theta = sin^{-1}\left(\frac{y_4}{s}\right)$



Point coordinates:

- Point 1:
  - $x = 0$
  - $y = 0$
- Point 2:
  - $x = 0$
  - $y = length\ of\ B$
- Point 3:
  - $x = A\cos(\alpha)$
  - $y = h = A\sin(\alpha)$
- Point 4:
  - $x = C\sin(\eta)$
  - $y = B + C\cos(\eta)$

Cross lengths:

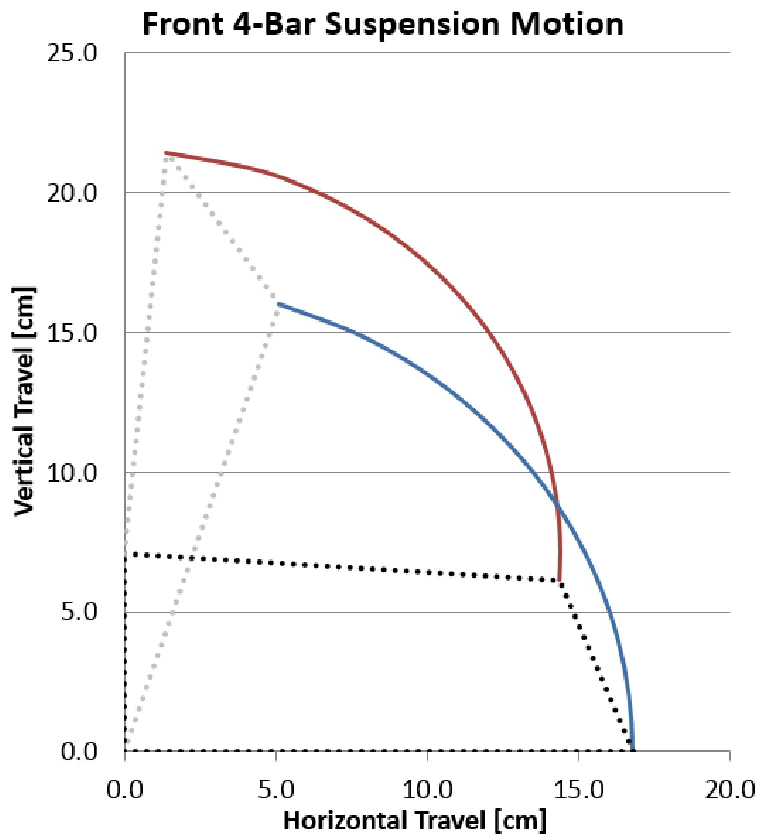
- $m = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}$
- $s = \sqrt{(x_4 - x_1)^2 + (y_4 - y_1)^2}$

Spring force:

- $F_s = spring\ preload + ks$
  - $k = linear\ spring\ constant$

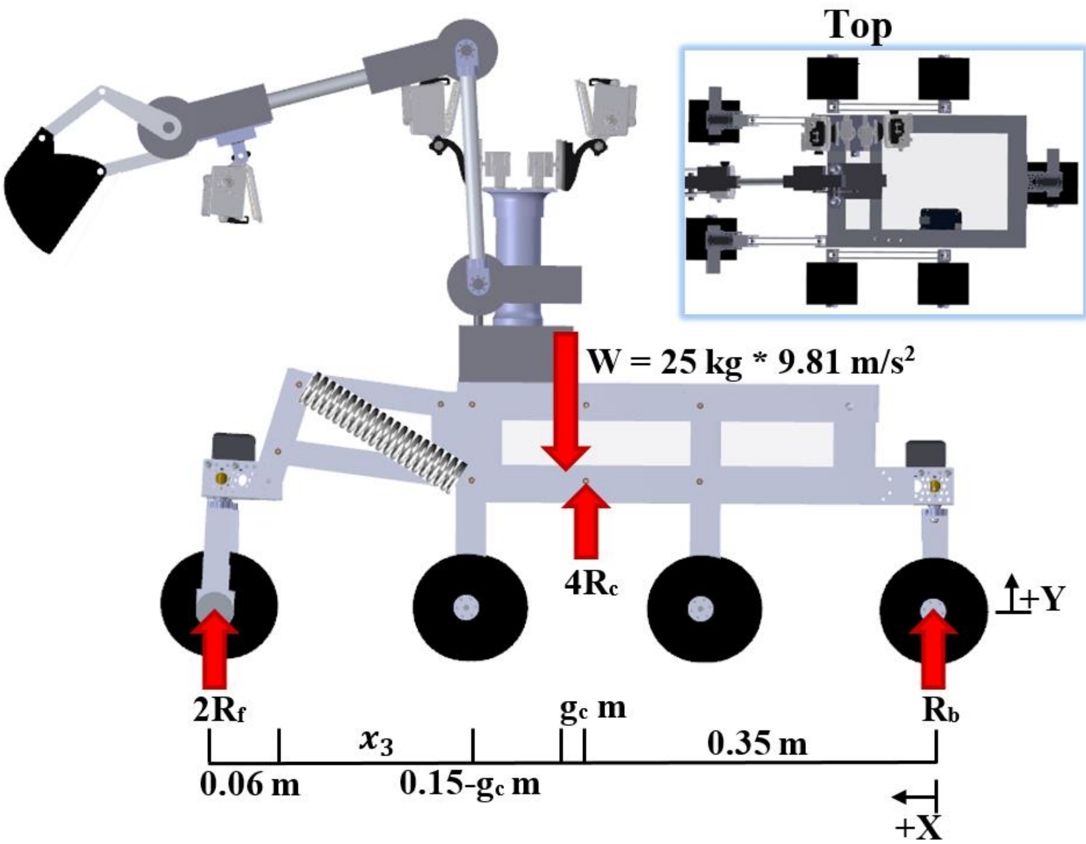
Reaction force on front wheels:

- $R_f = F_s sin(\theta)$



(black dots represent horizontal suspension position; gray dots represent extended suspension position)

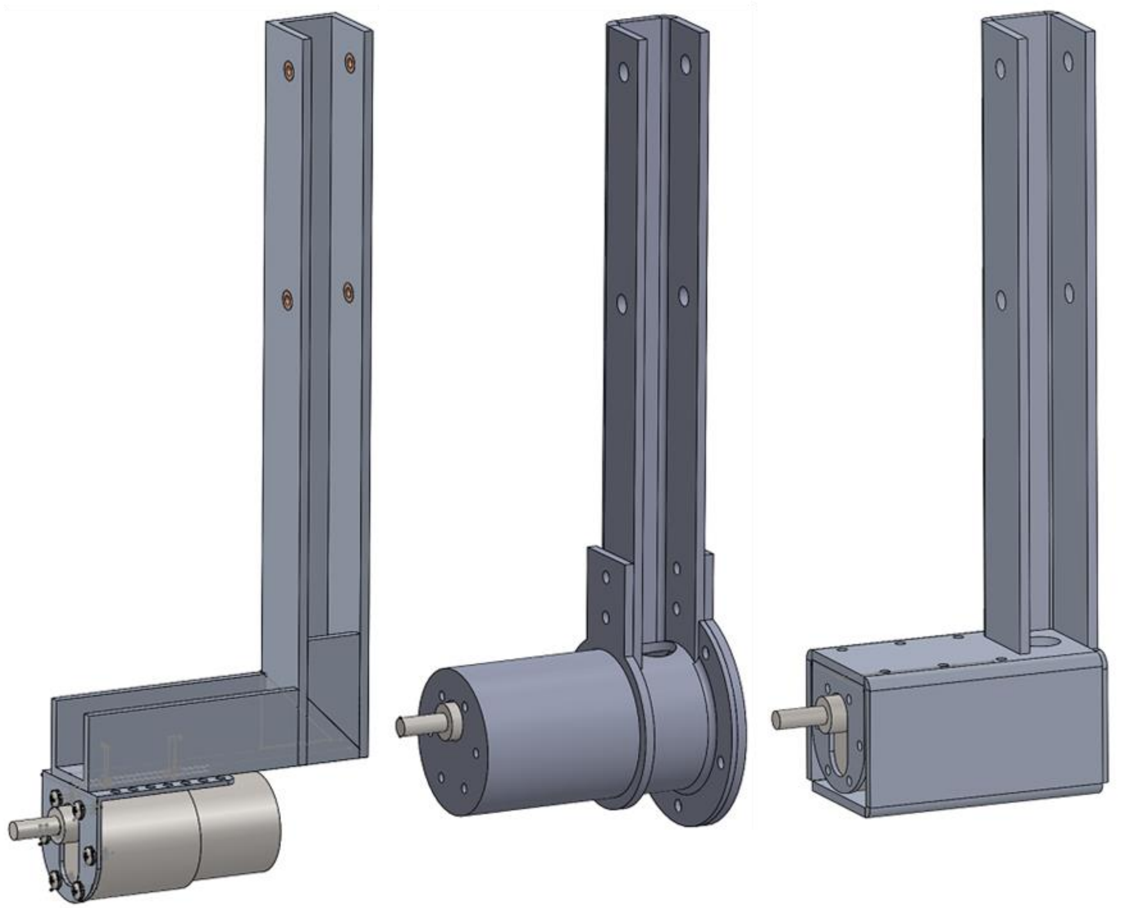
<u>Overall Rover Statics</u>:



Reaction force on each of the center wheels, R_c:

- Equilibrium of moments about the rear wheel:
  - $W(0.35 + g_c) - 0.35(4R_c) - 2R_f(0.56 + x_3) = 0$
  - $1.4R_c = W(0.35 + g_c) - 2R_f(0.56 + x_3)$
  - $R_c = \frac{W(0.35+g_c)-2R_f(0.56+x_3)}{1.4}$
- Reaction force on the rear wheel, R_b:
- Equilibrium of forces in y:
  - $2F_s + R_b + 4R_c - W = 0$
  - $R_b = W - 2R_f - 4R_c$

Appendix B: Motor Housings



Old Design Initial New Design Final New Design

The original suspension design was about two centimeters too wide for both rovers to fit within the design volume, and the wheel motors were partially exposed to the elements. To address both of these issues simultaneously, the motor mounting system was redesigned with a built-in motor housing that both reduces the rover's width and protect the motors from debris and water. The overall width of the rover was reduced by moving the motor more inward, which consequently calls for the motor to be fully enclosed by a housing since it would otherwise be sticking partly out the back of the wheel. This all new design essentially makes the motor housing and the channel out of just two pieces manufactured from sheet metal that are then welded together. What this concept allows for is simple manufacturing. This also allows for simple removal of the motor. A bracket used in the first rover will be attached to the motor which then attaches to the housing.

Appendix C: Rover Heat Transfer Model

Battery type: 20Ah $LiFePO_4$ battery

Generally accepted minimum efficiency: $\eta_{battery} = 90\%$ → 10% of 20Ah converted to heat

Maximum discharge rate is 16 Amps at 14.6 Volts ($P = IV = 233.6$ W), so the max heat generation at $\eta = 90\%$ is 23.36 W

- $R_{t,conv} = \frac{T_s - T_\infty}{q} = \frac{1}{hA} \rightarrow \boldsymbol{q = hA(T_s - T_\infty)} = 23.36\ W$
  - $where\ q = 23.36\ W$
  - $define\ T_{\infty_{max}} = 40℃$
  - $h = \frac{Nu_L k}{L}$
    - $\overline{Nu_L} = 0.664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}}, (Pr > 0.6)$
      - $Re = \frac{\rho v L}{\mu} = \frac{vL}{\nu}$
        - $\rho = fluid\ density$
        - $v = fluid\ velocity$
        - $\mu = fluid\ dynamic\ viscosity$
        - $\nu = fluid\ kinematic\ viscosity$
      - Pr comes from a table in heat transfer book
    - L is the characteristic length (length of battery)
    - k is the thermal conductivity of air at 30°C (0.0264 W/(mK))
  - $\bar{h} = \frac{k 0.664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}}}{L}$
    - $Re^{\frac{1}{2}} = \frac{\bar{h} L}{k * 0.664 * Pr^{\frac{1}{3}}}$
    - $Re = \left(\frac{\bar{h} L}{k * 0.664 * Pr^{\frac{1}{3}}}\right)^2$

Heat Transfer Model:

1. Define inputs:
   - Prandtl Number of air at 40° C $Pr = 0.711$
   - Fluid velocity $v = user\ defined$
   - Kinematic viscosity for air at 40° C $\nu_{air} = 16.97\ x\ 10^{-6}\ m^2/s$
   - Characteristic length (length of battery) $L = 0.25654\ m$
   - Thermal conductivity of air $k_{air} = 0.0271 \frac{W}{m℃}$
2. Calculate Reynold's Number:
   - $Re\ =\ \left(\frac{hL}{k} 0.664 Pr^{\frac{1}{3}}\right)^2$
3. Determine air velocity from Reynold's Number:
   - $v = Re \frac{\nu_{air}}{L}$
4. Calculate volumetric flow rate:
   - $V = A_c v$
     - where V is the volumetric flowrate of air
     - A_c is the cross sectional area through which the air is blown
     - v is the air velocity