2019 University of Portland Robotics Systems Engineering Paper

School: University of Portland (UP)

Team Name: UP Robotics
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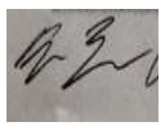

As the primary advisor for the University of Portland robotics club and NASA RMC Competition team, I certify that I have read and approve the submission of the team's systems engineering paper.

Enclosed,

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I. ABSTRACT

One of NASA's long-term goals has been to establish a permanent human presence on Mars. To achieve this, the ability to collect life sustaining resources is critical. According to NASA, mining icy regolith on Mars "will provide oxygen, water, and fuel for future off-world colonists" (Cannon). In support of this, the University of Portland Robotics Club will demonstrate the benefits and feasibility of using a single robot system consisting of the following physical components:

- A bucket-chain excavation system
- A conveyor-belt dumping system
- NASA inspired rocker-bogie suspension system.

Current control limitations for resource collection include the distance between Earth and Mars, autonomy, and the Mars environment. The distance causes a 20-minute delay of manual instructions between the robot and a station on Earth (Mission). Therefore, the robot must be autonomous which is a challenge given the terrain and environment on Mars. As such, the robot must be designed to be fault tolerant to maintain a working state. Autonomy consists of driving, excavation, and deposition as well as computer vision using Martian dust storm optimized 425 degree spherical 4.1K cameras to facilitate object location and path determination.

II. PURPOSE STATEMENT

The UP Robotics team has developed a robot which utilizes systems engineering: the robot's concept and design calls for electrical engineers, mechanical engineers, and computer science majors. The team chose to implement systems engineering because UP Robotics is a multidisciplinary team aiming to compete in the NASA Robotic Mining Competition. As such, the team integrates all groups: electrical engineers, mechanical engineers, and computer science majors, in a collaborative effort to build a robot which meets the needs of the NASA Robotic Mining Competition. The mechanical engineers developed the frame, suspension, conveyor-belt, and bucket-chain mechanisms. The electricals designed the power, remote operation, and hard-line connections. Finally, the computer science majors designed the computer hardware and software components. The team used the collaborate effort of all majors to integrate the electrical and mechanical parts together and provided the brainpower through computer science. This led to the creation of a successful product to present at the NASA Robotic Mining Competition.

The rules and requirements of the NASA Robotic Mining Competition acted as the team's customer needs. The competition urges participants to construct methods of mining icy regolith. Based on those standards, the UP Robotics team decided to build a robot that would fulfill the basic requirements of the NASA Robotic Mining Competition by incorporating the collaborate efforts of the multidisciplinary team. To create a robot that would reflect systems engineering in its development stage, the rules and objectives of the competition needed to be understood by the entire team to create a successful product. To that end, the team met collaboratively to ensure the product created would be cost-effective, high-quality, and created in a timely manner. The team has met the requirements of the competition, which are referenced in Table 3.

III. DESIGN

A. Philosophy

Robotic design decisions were chosen to maximize points in the On-Site Mining category of the competition. Therefore, robot mass and dimensions are of critical importance to pass inspection. Secondary objectives then include maximum excavation depth, autonomous travel, and high suspension travel. Optimizing secondary design functions is necessary in collection and return of icy regolith, and autonomous operation, which provide large point bonuses. Finally, tertiary design objectives include excavation and travel speed. Optimizing speed will increase potential icy regolith collected, resulting in additional points.

B. Updates

UP Robotics previously competed in the 2015 and 2019 NASA Robotic Mining Competitions. The 2015 team's design for that year was a two-robot design with one robot acting as the digger and the other acting as the transport and dumper. When competing, the transport robot would travel out to the dig site and deploy the digging robot. The digging robot utilized a bucket wheel to dig for material and load it into the transport robot. The transport robot would deposit the material at the dump site using a conveyer-belt and return to the dig site while the digging robot continued its excavation process.

The 2019 team utilized the bucket-chain and hopper/auger combination. The bucket-chain allowed for fast, reliable, and deep regolith excavation; however, the hopper and auger were unable to dump any gathered material. This was due to poor hopper design and large friction forces between the auger and shell. As a result, the 2019 team opted to keep the bucket-chain, while implementing improvements in its design, and to redesign a conveyor-belt originally used by the 2015 team.

Additionally, the robot frame was redesigned for simplicity, strength, and functional use with the bucket-chain and conveyor-belt. The electrical box was redesigned to maximize dust tolerance, reduce complexity and to add modular "plug-in-play" capabilities. Since the submission of the Pre-Systems Engineering Paper, nearly all deadlines were met with the exception of computer science and computer vision goals. Currently, the computer science team is still developing autonomous code.

IV. SYSTEM

A range of variables were considered when choosing the design of the excavation, containment, and dumping systems. Setting of weighted criteria, UP Robotics was able to decisively make educated decisions on which designs would be best suited for the 2019 NASA RMC and its updated rules. Depth of excavation and volume were deemed to be the most essential criteria for the excavator and containment systems, respectively. Mass and size were very flexible as the robot was significantly underweight for the 2019 competition. A bucket-chain was chosen as the excavation system for its volume, size, and ability to reach a variety of depths, while also having shown durability and feasibility in the 2019 competition. A conveyor-belt was chosen for the containment system as it scored highest in every criteria.

Table 1: Excavator

	Bucket Chain	Auger	Bucket Wheel
Depth of Excavation (Weight: 30)	0.8	0.8	0.4
Weight (Weight: 20)	0.4	0.2	0.4
Size (Weight: 10)	0.6	0.4	0.2
Complexity (Weight: 10)	0.2	0.4	0.6
Manufacturability (Weight: 20)	0.4	0.3	0.4
Volume (Weight: 10)	0.8	0.6	0.6
Total	56	43	42

Table 2: Deposition

	Hopper & Auger	Conveyor
Volume (Weight: 40)	0.4	0.4
Weight (Weight: 20)	0.2	0.6
Manufacturability (Weight: 20)	0.2	0.5
Complexity (Weight: 20)	0.5	0.5
Total	34	48

A. Requirements and Verification

The UP robot is defined by necessary and supplementary requirements. Necessary requirements were derived from the 2019 NASA RMC Rules and Rubrics (National). Supplementary requirements are shown in Table 3.

Table 3: UP Robotics Supplementary Requirements

Requirement	Discipline
System shall contain excavation and deposition systems	ME
System shall be capable of excavating gravel simulant	ME
System shall be capable of traversing over arena obstacles	ME
System shall be electrically safe to operate	EE
System shall have a completely enclosed electrical box	EE
System wiring, and electrical component layout will provide efficient and non-interfering functions	EE
System shall have fully-autonomous functionality for excavating and depositing material	CS
System shall have fully-autonomous functionality for unpacking and packing the robot	CS
System shall have at least semi-autonomous functionality for driving, mapping the environment, and detecting/avoiding obstacles	CS

To ensure reliability and integration, a test bed was created with one of each of the robot’s main components such as the Arduinos, the Raspberry Pi (R-Pi), encoders, and Sabertooth motor controllers. The software interfaces for the components were tested and debugged using the testbed before the robot was wired with the components for testing on the robot.

To assure that the robot satisfies the requirements above, extensive safety checks have been performed on the rover's motions, unpacking and repacking the wheels and moving them into correct orientations. Code has been written to ensure the encoders provide the expected output and code has been written that will calculate how far away the articulation sensor's zero axis is away from their ideal orientation and will report to the user in a semi-user-friendly way. Excavation and deposition have also been extensively tested and practiced. During the initial testing phases, two team members were ready to step in and push the manual e-stop, the testing process has been further refined in the construction of a test mount that suspends the robot above the ground allowing for wheel, suspension, bucket-chain, and conveyor testing. By extensively testing all functionality as the rover is being constructed, we believe it is realistic to satisfy all safety requirements provided.

B. Hierarchy and Concept of Operations

Physical system

The following sections describe the physical, electrical, and software systems of the UP Robotics Rover.

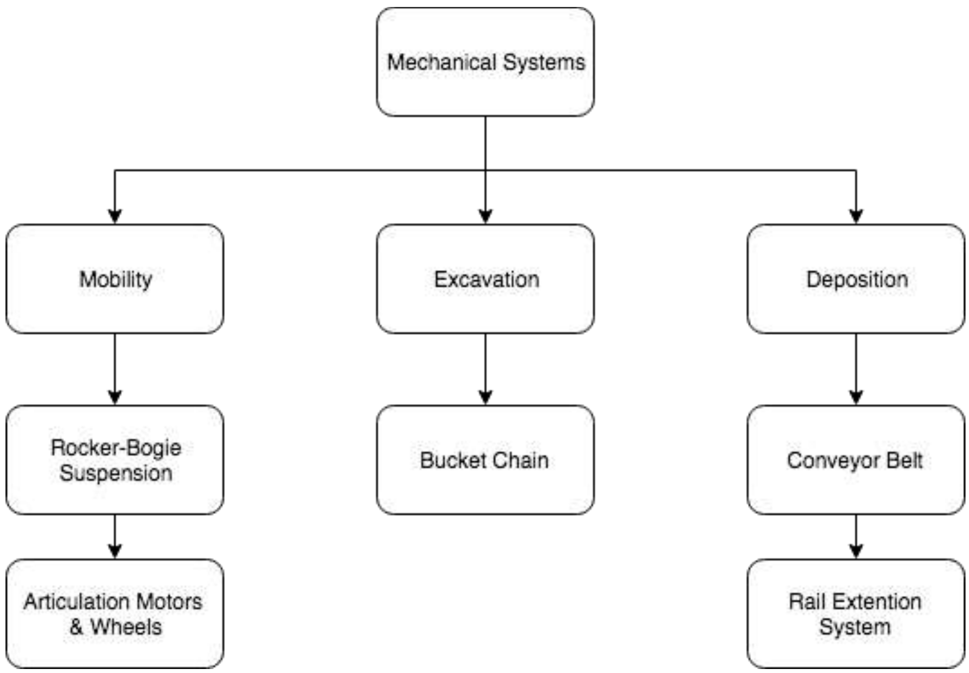


Figure 1: Physical System Hierarchy

For the 2019 robot to successfully meet all competition requirements, there are three overarching physical assemblies. The mobility system, the excavation system, and the collection/deposition system.

The mobility system, consisting of the wheels, rocker-bogie suspension, and structural frame, was chosen to optimize system robustness and traversal ability. Compared to other suspension systems, which are prone to pitch and roll on undulating terrain, the rocker-bogie utilizes an averaging differential to provide a stable ride over uneven terrain by equalizing the rovers mass across all six (6) wheels. Both the suspension system and the frame to which it is mounted, could be made robust by varying member thickness, placement, and quantity. Criteria for alternative mobility designs are shown in Table 4.

Table 4: Transport Decision Matrix

Criteria	**H-Frame**	**Rocker bogie**
Strength (Wt=25)	0.5	0.7
Stability (Wt=25)	0.3	0.7
Traversability (Wt=30)	0.4	0.8
Mass (Wt=20)	0.8	0.5
Simplicity (Wt=10)	0.8	0.2
Manufacturability (Wt=15)	0.7	0.4
Total	66.5	77

In order to maximize the effective life-span of a remote device, the device must be able to withstand operation without maintenance. During its operation, unforeseen circumstances may ask the device to operate in conditions which it was not designed to handle. Therefore, over-engineering in the mobility system is critical. Reliance on sensor systems to guide the Rover around obstacles could fail in dusty environments, resulting in critical mission failure. The Rocker-Bogie suspension system allows for continued operation through obstacles in the event of such a failure.

A major improvement for the 2019 UP Robotics Rover was the design and construction of an all new structural frame. It was determined that the dusty environment found both on Mars and the RMC competition arena presents some unique design considerations. In order to combat dust accumulation in the frame and to protect bolt locations, a sealed frame was selected. Materials considered for the construction of the new frame were a Carbon Fiber tube frame and a welded Aluminum frame. Table 5 compares the criteria of these alternatives.

Table 5: Decision Matrix for frame materials

Criteria	Carbon Fiber	Aluminum
Mass (Wt=40)	0.9	0.7
Complexity (Wt=20)	0.7	0.6
Rigidity (Wt=60)	0.9	0.7
Manufacturability (Wt=30)	0.3	0.9
Cost (Wt = 10)	0.2	0.9
Dust Tolerance (Wt=20)	0.3	0.6
Total	121	131

Although carbon fiber had many advantages, an aluminum welded frame was chosen by the previous team for its simplicity, manufacturability, and ease of future modification. The construction of a carbon fiber frame would have required aluminum to connect the tubes in the desired geometry. These connections would have offset the weight savings achieved by the carbon fiber and added to the difficulty and duration of manufacturing.

A crucial component of the Mobility System, the six driven wheels must support the weight of the Rover and the excavated payload as it traverses over the obstacle ridden regolith surface. Proposed material alternatives and designs included 3D printed ABS, welded aluminum sheet, and a hybrid of carbon fiber and aluminum. All potential designs for this system were evaluated on their strength, durability, manufacturability, and overall weight. Two of the alternatives are shown below in Figures 2 and 3. The decision matrix for the wheels are shown in Table 6.

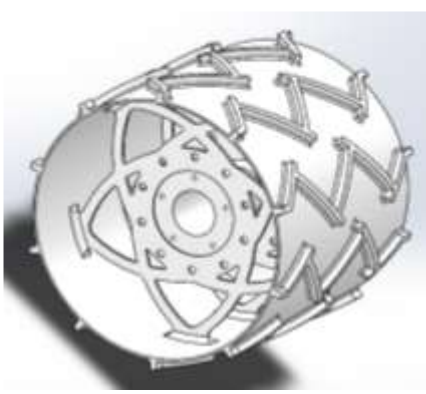


Figure 2: ABS wheel alternative

Figure 3: Hybrid wheel alternative.

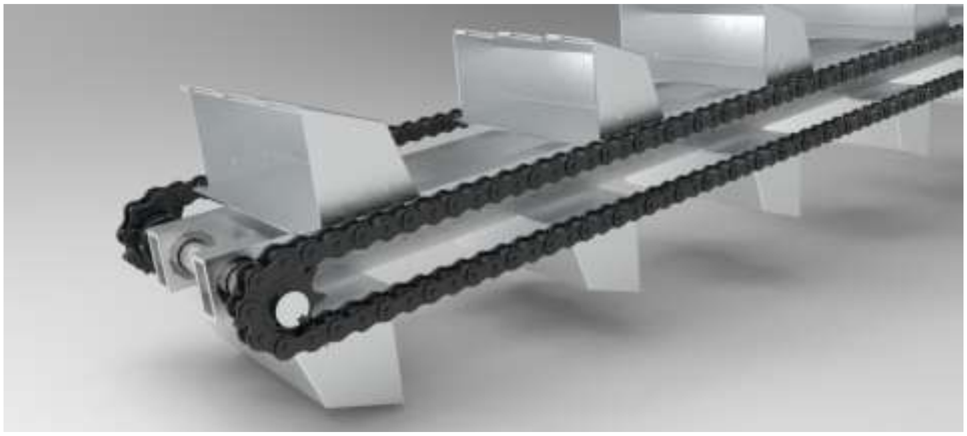
Table 6: Transport Wheel Decision Matrix

Criteria	ABS	Aluminum	Hybrid
Strength (Wt=35)	0.5	0.6	0.9
Durability (Wt=35)	0.4	0.6	0.8
Manufacturability (Wt=15)	0.9	0.6	0.5
Weight (Wt=20)	0.7	0.6	0.7
Total	59	63	81

As determined by the decision matrix, the Hybrid Carbon Fiber and Aluminum wheels were chosen. Prototype models of both alternatives, the 3D printed and Aluminum wheels, were also contracted to facilitate physical comparison. The Hybrid wheel designed again proved to be superior and the remaining wheels were manufactured.

After analysis of multiple systems, the results of which are detailed in Table 1, the Bucket Chain excavation system was chosen. Centrally mounted within the robot frame to maximize space utilization, the bucket chain system is 110 cm long and reaches a maximum excavation depth of 45 cm (maximum possible depth as per RMC 2019 Rules) when fully deployed. This system is deployed using a dual motor lowering and raising system. NEMA 23 stepper motors equipped with single thread 1.8 degree lead screws provide the necessary accuracy and torque to facilitate this operation. The bucket chain itself is driven by a NEMA 34 stepper motor and a custom designed 20:1 worm-wheel gearbox. When powered, buckets mounted to the chain will collect regolith and gravel and deposit said material onto the conveyor system upon reaching the top of the chain. The chain features a tensioning system in order to eliminate the possibility of slippage and to assist in chain removal and maintenance. The constructed bucket chain system can be seen in Figure 4.

(A)



(B)

Figure 4: (A) Bucket Chain Digging System (B) CAD Model of UP Rover Bucket Chain

The final system required for Rover operation, the collection/deposition system selected was a dual use conveyor belt. The decision matrix detailing this conclusion is in Figure 2. Conveyor system operation consists of multiple steps. While the rover is in its starting, "packed", position, the conveyor remains inside the rover, mounted directly above the wheels. After competition of the "unpacking" process, the conveyor is guided out from rover body by dual lead screws and a supporting rail system. Once reaching its fully extended position, the 1-meter long conveyor reaches a maximum height of 50 cm, a height at which the conveyor is fully capable of depositing excavated material into the scoring hopper. As the bucket chain deposits material on to the conveyor, it is held in place by paddles, which are mounted directly to the conveyor belt. As the belt is loaded, integrated motors advance the belt in 10 cm increments to expose additional collection space.

As the RMC Rules specify, collection and deposition of the BP-1 regolith simulant does not score mining points, therefore, to maximize each collection run, the BP-1 must be filtered, leaving only the valuable icy regolith. To achieve this, the conveyor belt was constructed from a high strength plastic mesh. After testing of multiple mesh sizes, a mesh with hole size of 2mm x 2mm was chosen for its effectiveness at filtering the BP-1 simulant, as well as its highly flexible construction. The conveyor belt frame was constructed from carbon fiber I-beams and features six (6) passive rollers constructed from carbon fiber tube. These materials were chosen to minimize addition mass while maintaining rigidity. The conveyor belt collection and deposition system are shown both in its packed and unpacked states in Figures 5 and 6 respectively.

The complete UP Robotics Rover, undergoing testing with all systems integrated, is shown in Figure 7.


Figure 5: UP Rover CAD in a semi-“Packed” State

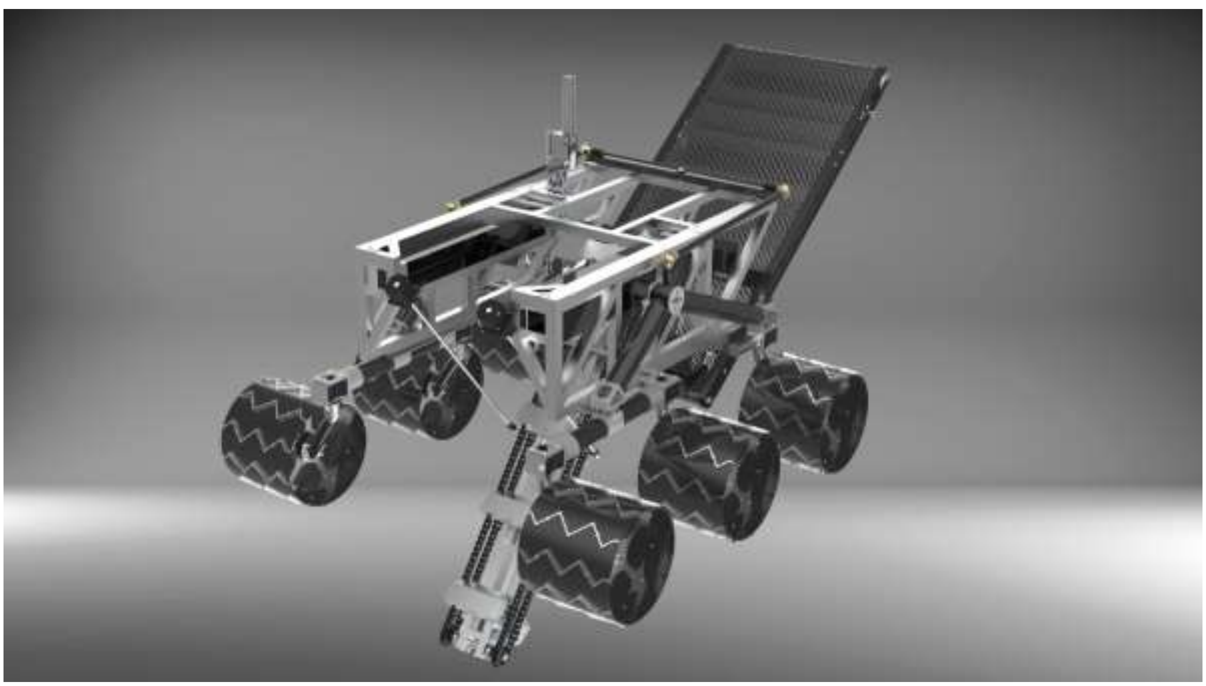


Figure 5: UP Rover CAD in a fully “Unpacked” State

Figure 7: Fully integrated UP Rover undergoing testing

Physical system

The electrical section is broken into: (1) power for the subsystem and (2) power consumption feedback.

(1) Power subsystem

To power the Rover, various battery sources were considered including: Alkaline, Lead-Acid, Nickel-Cadmium, Nickel-Metal Hydride, and Lithium.

The following criterion was kept in mind: safety, reliability, and weight. In order to maximize reliability, efficiency, and safety across all systems, the rover was designed to run off both 14.8 V and 29.6 V power supplies. The dual voltage system was selected after careful consideration of the competition goals. The Mobility system and Deposition system rely on the 14.8 V system, and the Excavation system utilizes the 29.6 V system. This setup enables the rover to continue excavation through the entirety of its power supply while leaving the Mobility system with power to return to the scoring hopper and deposit the excavated material. Lithium polymer batteries were selected to save weight because they offer the highest specific energy as shown below in Figure 7. Lithium batteries were also chosen because of their desirable discharge curves. Battery discharge curves also demonstrated that lithium is able to maintain a more reliable voltage for the duration of its charge cycle.

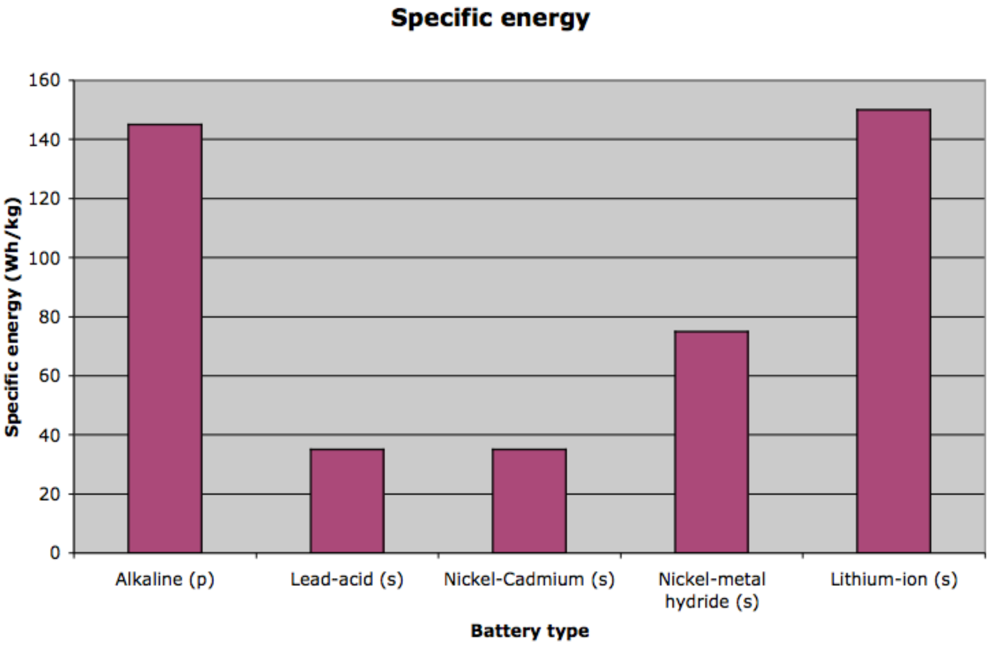


Figure 6: Alkaline and Lithium-ion batteries are superior choices for robotics applications due to their high specific energy

(2) Power consumption feedback

To improve power system reliability, it is necessary to protect vital components from dangerous current levels. To address this problem, it was determined necessary to send live current measurements to the control system.

One option to solve the problem evaluated was to use off-the-shelf power monitors with logging capability and send that data to the control station. A second alternative was to utilize a Hall Effect current sensor to measure the current across each individual device on the device and send that data to the control system.

The Hall Effect sensors were selected due to their ability to measure each individual motor. While requiring a more comprehensive installation process, monitoring every motor allows for detection of potentially damaging stalls and enables single motor shutdown in the occurrence of a stall, instead of broad subsystem shutdown. Due to RMC Rules, an off the shelf power monitor was also included, but the models selected did not require logging capability. A secondary protection circuit with a slow burn fuse was also designed for redundancy, if, in the case of a stall, the control system and hall effect sensors were unable to correct the issue.

Control system

The control system hierarchy is shown in Figure 8.

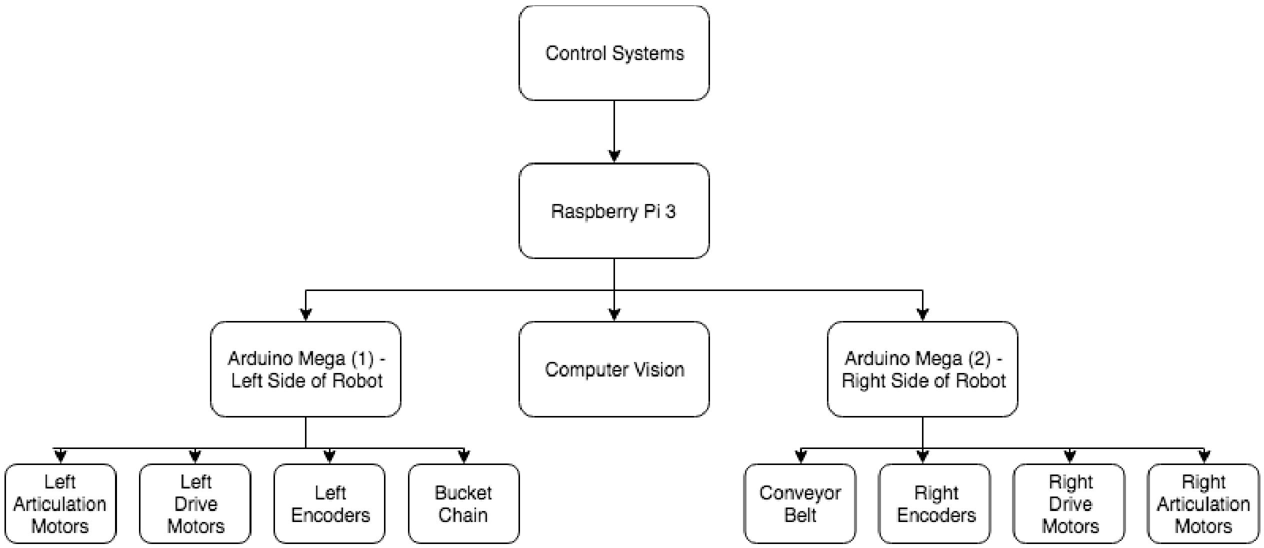


Figure 8: Control system hierarchy

Main control of the robot will be a single Raspberry Pi 3 (Rpi) which will run a state machine and make movement decisions based on data from the computer vision and feedback from the Arduino Mega. The Arduino Mega must carry out commands from the Rpi and provide feedback on task completion and errors. The dual computer vision cameras will pass an array of data to the Rpi directly over USB that describes a spherical image of the robot's environment. This will allow the Rpi to create a path for the Rover which avoids obstacles while continuing to move towards the mining area. Commands will then be sent to both Arduino Megas to carry out the determined path. Addition commands allow the Arduinos to commence with Excavation or Deposition. The states for the robot are detailed in Table 7 and a state machine flow chart can be seen in Figure 9.

Table 7: State machine operations

State	Description	Next State	Transition
Start	Initialize robot by unpacking the wheels and preparing for movement	ScanDig	All wheels are in the drive position, the digger and dumper systems are stored, and the computer vision mount is ready for scanning
Move	Execute commands for movement to follow path created for the robot	ScanDig ScanDump	ScanDig if conveyor is empty ScanDump if conveyor is full
ScanDump	Scan using computer vision and create a safe path for the robot towards the collection bin by looking for the marker on the collection bin	Move Dump	Move if scan was successful and path was created Dump if reached dumping site
ScanDig	Scan using computer vision and create a safe path for the robot towards the excavation site by checking the distance and angle from the marker on the collection bin	Move Dig	Move if scan successful and path was created Dig if reached the excavation site
DockingBin	Dock the robot to the collection bin for depositing material	Dump	Robot is docked to the collection bin
Dump	Deposit the regolith into the collection bin	ScanDig	Conveyor is empty
Dig	Deploy the excavation system and mine icy regolith until the conveyor is full	ScanDump	Excavation system is retracted and conveyor contains regolith

Reflective tape will be placed on the collection bin for the robot to determine its location. When the robot is travelling to the collection bin, the robot will look for paths clear of obstacles that lead towards the marker. When the robot is travelling to the excavation site, the robot will first move to the middle of the dumping site in front of the collection bin by using the marker then proceed by looking for paths clear of obstacles and then tracking how far the robot has moved from the bin until it reaches an appropriate distance indicating the robot is at the excavation site. To ensure that the robot is in the excavation site, the robot will take another distance reading to the collection bin. If the robot is in the excavation site then it will begin digging; otherwise, the robot will move and take another reading to the collection bin until it is in the excavation site.

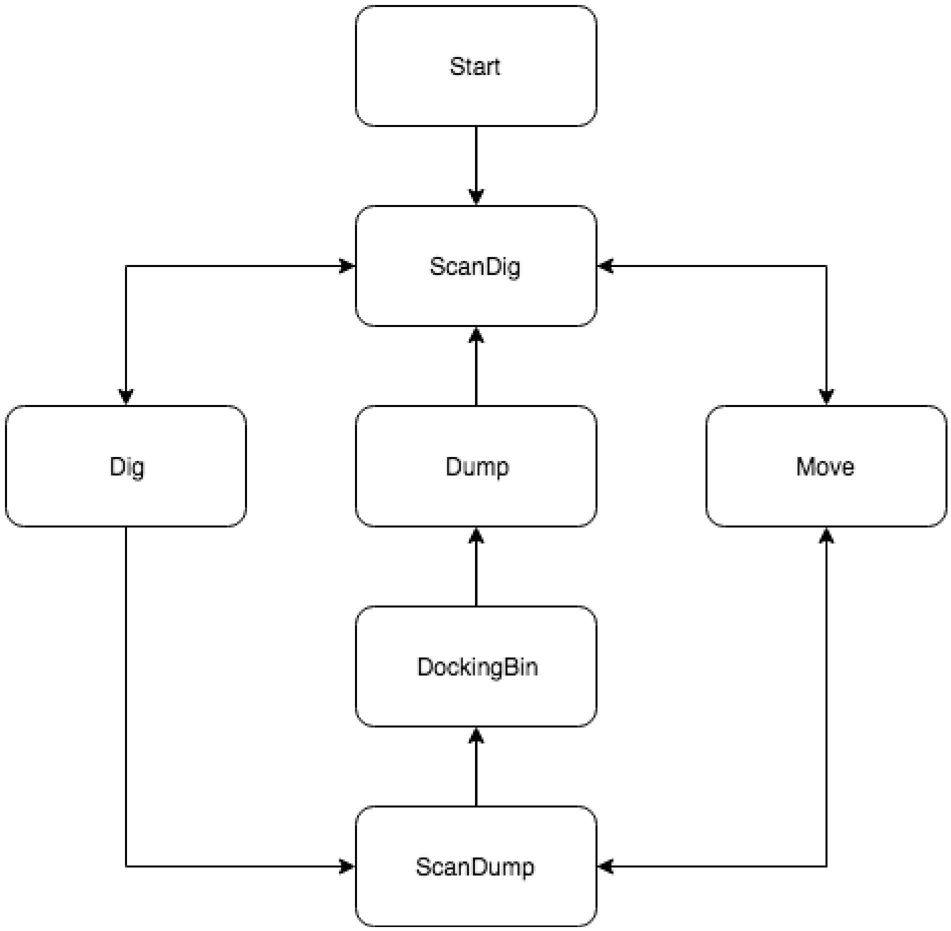


Figure 7: State Machine flow chart

C. Interfaces

ROS publishers and subscribers are used for communication between the Rpi and the Arduinos. The states for scanning publish ScanCommand messages to the Scan topic to indicate whether the robot should perform a forward scan of the environment or a backwards scan towards the marker on the collection bin. The Arduino Uno subscribes to this topic and carries out the commands in the message. The DataServer on the Rpi publishes MovementCommand messages to the MovementCommand topic. The Arduino Mega subscribes to this topic and carries out the commands in the message which includes actions such as driving, excavating, and depositing. The Arduino Mega will publish ArduinoMessage messages to the ArduinoFeedback topic. The Feedback Handler and the DataServer will subscribe to this topic which will allow the main control in the Rpi to know when the robot has completed the last assigned task such as driving forward or digging. The ArduinoFeedback message also includes error messages which allow the main control to handle the errors. See Table 11 in the Reliability section for examples of error handling. Figure 10 is a diagram of the software system components and communication links. See Tables 8, 9, and 10 to see the MovementCommand, ArduinoMessage, and ScanCommand messages respectively.

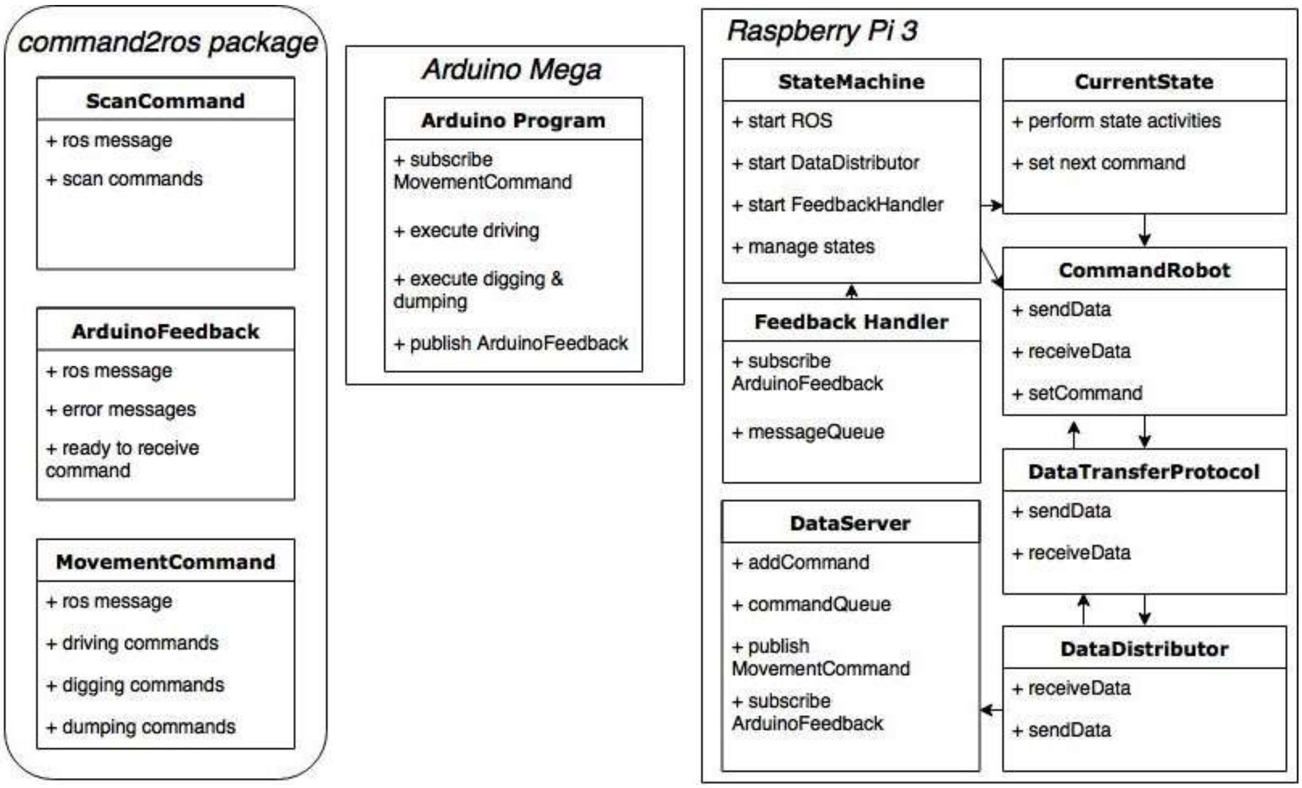


Figure 8: Software System Communications

Table 8: MovementCommand

Type	Command	Description
Int32	serialID	Message ID
Bool	manual	Whether the robot is being controlled manually
Int32	manualDrive	Whether to drive forwards, backwards, or not at all
Int32	manualTurn	Whether to turn right, left, or not at all
Float32	driveDist	Distance to drive forward
Int32	turn	Number of degrees to turn the robot
Bool	dig	Begin excavation sequence
Bool	dump	Begin dumping sequence
Bool	packin	Pack the wheels under the robot
Bool	eStop	Stop all movement and do not move unless eStop is removed
Bool	Pause	Stop all movement and resume last command when pause is false
Bool	cancel	Cancel the last command, stop all movement, and continue listening for more movement commands

Table 9: ArduinoMessage

Type	Command	Description
Int32	messageID	Message ID of ArduinoFeedback
Int32	serialID	Message ID of MovementCommand this message is providing feedback for
Bool	ready	Whether the robot is ready to receive commands for driving, digging, dumping
String	progress	Human readable message on progress carrying out the last command
Bool	errorDriving	Notify Rpi to handle drive error
Bool	errorDigging	Notify Rpi to handle digging error
Bool	errorDumping	Notify Rpi to handle dumping error
Bool	errorTurning	Notify Rpi to handle turning error

Table 10: ScanCommand

Type	Command	Description
Int32	serialID	Message ID
Bool	scan	If true, scan for dig site, if false, scan for the deposition site

D. Reliability

The complete system was designed to be reliable and fault tolerant to the many challenges from the environment and integration of the components. The following sections detail how and why the UP Robotics Rover is reliable.

i. Software

To ensure the successful completion of the mining mission, the UP MARS will need to be able to handle any challenges in the environment or abnormalities. To handle these problems the Arduino will provide this feedback to the Rpi about whether the robot is unable to complete or carry out a command. The Rpi will then rescan the robot's environment and determine what action to take. Table 11 shows examples of the most likely scenarios the robot may encounter and how the software system will handle them.

Table 11: Software Reliability Examples

Scenario	Resolution
A rock has been hit and a wheel is not turning. This has been detected from an overdraw of current.	Arduino will stop the wheel and notify the Rpi. The Rpi will move the robot to its position before the incident and rescan to decide a new path that is different from the command which led to the incident.
The excavation system stalls which has been detected from an overdraw of current.	Arduino will stop the motor, restore the digger to the resting position and notify the Rpi. The Rpi will attempt to redeploy the excavation system. If another stall occurs, the same sequence of resolution steps will be carried out but instead of redeploying the excavation system immediately, the Rpi will first move the robot to a different excavation area.
The dumping system fails to fully extend due to a stall which has been detected from an overdraw of current.	Arduino will run the conveyor extension steppers in reverse for a half turn to dislodge the item, then continue to extend the conveyor system.

For safety and emergency, the UP Robotics software system will have emergency stop (e-stop) functionality. The e-stop will stop all motors, disallow all commands to motors that would put them into motion, and send the Arduino into a permanent sleep. The software also has stop/pause command which will allow the robot to stop executing the current command and "pause" stopping the motors and sending the Arduino to sleep while stopped, in the paused state the Arduino would continue to listen for a command to resume normal function, upon which it will resume its command.

Motor feedback

As articulation motors move through the environment, inconsistencies in the motors and their attached gearboxes leads to inherent inaccuracy when motors are told by the control system to rotate a specified amount. To solve this problem, the main control system will provide a distance to drive and degrees to turn which will be handled by the Arduino. The Arduino will provide feedback on whether an operation was able to be fully completed to allow the main control system to make movement decisions.

Alternatives considered to address the problem included potentiometers, magnetic encoders and optical encoders. Potentiometers did not meet the requirements because they were unable to provide the degrees of rotation and shaft diameters necessary. Absolute magnetic encoders were selected due to their high accuracy and better durability than optical encoders at a comparable cost. It was important to use absolute encoders due to their ability to set a "zero", this eliminates the requirement to always start the Rover with the articulation joints in a set orientation.

Motor stall protection

Reliability of the electrical system is of great importance for a successful Rover. In the case that the device encounters an obstacle that it is unable to drive over, a drive motor will stall, drawing a large amount of current from the power system. Although the electrical system is designed to handle this situation, if it persists, the stall would cause undue drain on the batteries and potentially damage the power system. Due to this risk, a system needed to be developed in order to detect and rectify a stall condition.

To solve this problem, the subsystem must accomplish two goals: (1) cut power to each drive motor in the event of a stall condition, and (2) measure motor current draw to detect a stall condition.

Non-resettable fuses, resettable fuses, and relays were considered to achieve power cutoff. Selection criteria for power cutoff included cost, reliability, and system control. System control refers to the ability of the computer system to directly control the device. Weights were given to each of these based upon their efficacy in solving the problem, and a summary of the decision-making process is provided in Table 12.

Table 12: Power Cutoff Decision Matrix

Decision Factor	**Non-resettable fuses**	**resettable fuses**	**relays**
Resettable (wt = 50)	0	1	1
Cost (wt = 5)	0.9	0.5	0.5
Reliability (wt = 15)	1	0.85	0.5
System Control (wt = 25)	0	0	1
Total	19.5	65	85

As shown in the table, relays were selected because they provide the most reliable and computer controllable method of cutting power to the motor.

E. Technical Budgets

Table 13: Technical Budget Allocations

Technical Budget Items	Initial Target	Individual System Allocations
Mass	Under 70 kg	Drive System: 30 kg Digging System: 15 kg Dumping System: 10 kg Electronics: 8 kg Batteries: 2 kg
Size	1.5m x 0.75m x 0.75m	Packed Wheels: 1.2 m x 0.75 m x 0.35 m Frame: 1.5 m x 0.75 m x 0.4 m
Maximum excavation depth	45 cm (Maximum Depth)	Bucket Chain Length: 100 cm Raising and Lowering System Length: 100 cm
Autonomous operation	500 pts (Fully Autonomous)	Drive System: 360° Camera, encoders and current sensors on motors Digging System: current sensor on motor Dumping System: force sensor to determine weight
Suspension Travel	30 cm	Wheel Diameter: 30.5 cm Bogie Length: 50 cm
Excavation Speed	2250 cm^3/min	Buckets: 10 Bucket Volume at ½ fill: 375 cm^3 Chain Sprocket Speed: 60 rpm
Travel Time to Mining Area	Less than or equal to 1 minute	Unpacking: 10s Direction Discovery: 10s Travel: 30s

The power draw by a wheel motor was determined to analyze the expected current draw by each of the six drive motors. To assist calculation, several assumptions were made. The rolling resistance coefficient was assumed to be 0.5, the maximum mas was 100 kg, and desired speed was 1 meter per second. The required power calculated to move the Rover when fully loaded was 0.34 kw. To determine the max current draw by each motor when under full load, the total power divided equally between each wheel. As a result, each wheel motor needed to provide 56 watts of power to move the Rover at the operational speed. Using a simple conversion, each drive motor required five amps to operate at full load. The Arduino microcontrollers use between 40 and 50 mA per pin used. Under these conditions, the Arduino Mega controlling the motors would be expected to use between 320 and 400. Each of the six encoders is expected to use 16 to 20 mA to operate for a total of 96 to 120 mA. When the robot moving with a full load of gravel, the expected current draw is 30.52 A. As the batteries chosen were rated at 50C with 7200 mAh, the current drawn is significantly less than the recommended for one battery, with an expected life between before needing charging is 12 minutes. As the robot is not expected to be running under these circumstances for extended periods of time, actual operational duration will be longer.

V. MAJOR REVIEWS

Table 13 shows the general major reviews for the entire robot system and project.

Table 13: General Major Reviews

Review	**Summary**	**Date**
System Requirements Review	• Reviewed and discussed NASA RMC Rules and Regulations • Discussed project scope and compiled lists of physical, electrical, and software systems requirements • Discussed budget costs and fund raising	Sept. 7, 2019
Preliminary Design Review	• Reviewed multiple transportation, excavation, and depositing designs • Reviewed multiple software communication systems • Reviewed multiple electrical systems • Decided on systems and approved budget • Completed Pre-Systems Engineering Paper	Nov. 21, 2019
Critical Design Review	• Updated schedule to reflect the current status of the project • Redesigned sub-components of the system	Feb. 13, 2019

VI. SCHEDULE OF WORK

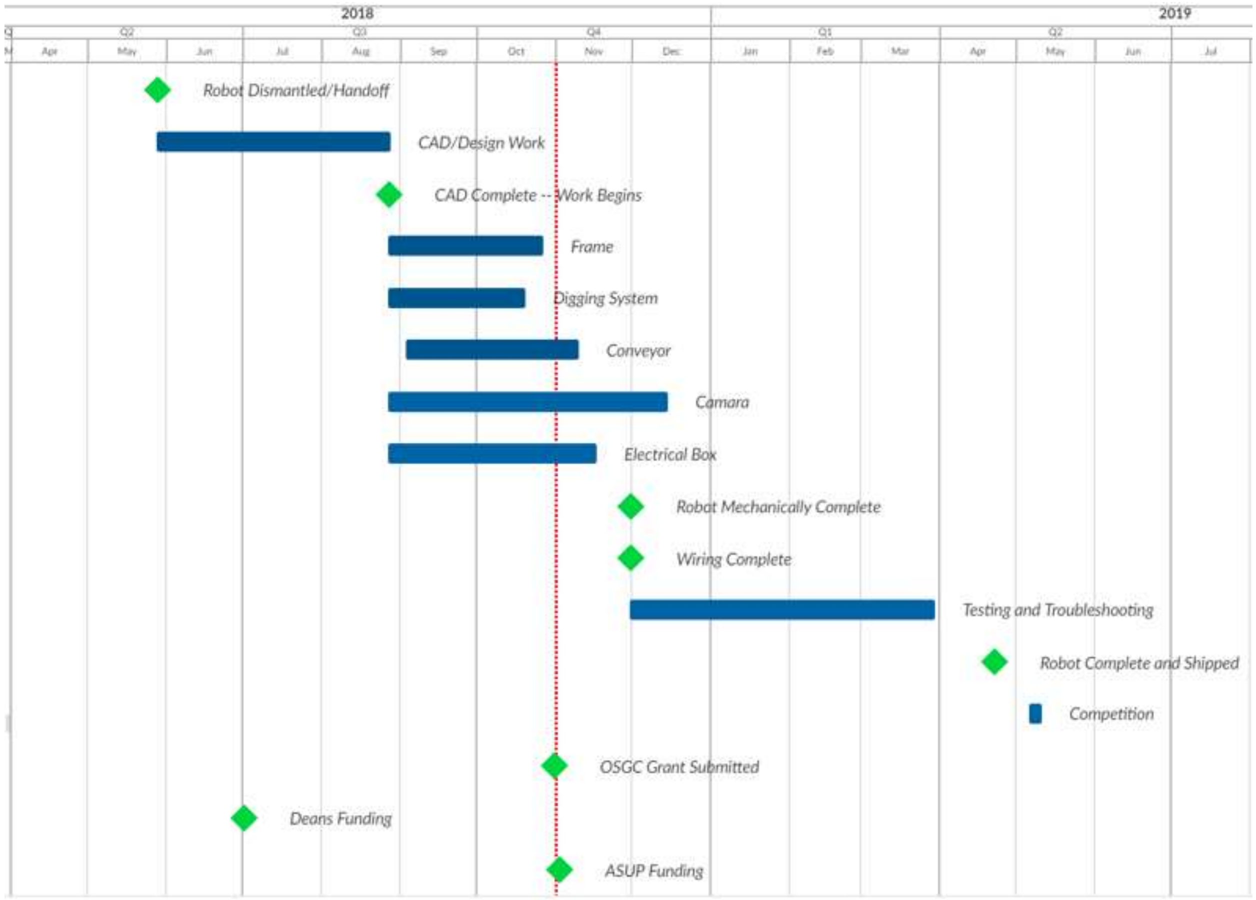


Figure 11: 2018-19 UP Robotics Task Schedule

The University of Portland (UP) team began brainstorming new ideas and systems immediately following the final competition run of the 2018 RMC. Upon returning to Portland, new roles were established and meetings were held to create a rough schedule and design strategy. The 2019 project began on May 27th, 2018 and will conclude on May 13th, 2019 when the Rover will officially roll over to next year's team. This year, the main objective, as shown in the provided Gantt Chart, is completing the mechanical design as early as possible, giving the computer science and electrical engineering teams plenty of time to test and troubleshoot. This will also allow the team to fine-tune all processes, a luxury the previous design team could not afford.

The mechanical team is especially focused on maintaining accuracy in the robot's CAD model to avoid overlooks and implement lean manufacturing practices: elimination of wasted time, materials, and effort. Having a central vision of a completed robot allows for preemptive discussion among group members, preventing schedule slips and unforeseen road blocks. For new additions to the robotics team, updated CAD files are able bridge the learning gap and help the newer members familiarize themselves with the team's goals.

In following with lean practices, one team member is assigned the weekly responsibility of tracking all work done on the robot and recording what constraints, if any, impacted the production of the team. Additionally, this “Weekly Workplan” document tracks the frequency of constraints allowing the group to mitigate them in the future. Paired with the Gantt Chart, this tool helps minimize schedule slips and allows for a more efficient scheduling and time prediction of tasks. In the event that project tasks fall behind schedule, the Weekly Workplan allows for a clear reallocation of manpower to ensure the projects timely completion. The Gantt Chart above in Figure 11 shows the expected completion date for all major deliverables related to the robot and RMC.

VII. COST BUDGET

The UP Robotics Rover project has received significant funding from various sources. As an official University of Portland Club, the project has been supported by club funding through the Associated Students of the University of Portland (ASUP). The project has also received funding from the Shiley School of Engineering Dean's fund, the Oregon Space Grant Consortium (OSGC) and individual donations through the University of Portland. For the 2019 team, the estimated cost of the project including reused parts from the previous team is $30,267.69. The general breakdown of the project funding and total costs is shown in Table 15. For the full detailed budget by line item and source see appendix A. Note that the full budget will differ from the Pre-Systems Engineering budget to reflect the decrease in travel expenses.

Table 15: Project Funding and Total Costs

2015 reused parts	2019 Funding from ASUP	2019 Funding from Dean's Fund	2019 Funding from OSGC	2019 Funding from donations	2019 robot cost	2019 team overall cost
$13,252.32	$6,453.00	$10,000	$4,975.00	$788	$18,093.89	$30,267.69

VIII. REFERENCES

Cannon, Rob. RMC Information. National Aeronautics and Space Administration. Sept. 20, 2018 https://www.nasa.gov/offices/education/centers/kennedy/technology/nasarmc.html

Engineering ToolBox, (2008). *Rolling Resistance*. [online] Available at: https://www.engineeringtoolbox.com/rolling-friction-resistance-d_1303.html 6 Mar. 2019.

"Sources (More)." *Tire Friction and Rolling Coefficients*, hpwizard.com/tire-friction-coefficient.html.

Mission Timeline: Surface Operations. NASA JPL, 21 Deb 2018, https://mars.jpl.nasa.gov/mer/mission/tl_surface_nav.html

National Aeronautics and Space Administration (2019). *RMC 2019 Rules and Rubrics*.

Kurtus, Ron. "Coefficient of Rolling Friction." *School for Champions*, 20 Nov. 2016, www.school-for-champions.com/science/friction_rolling_coefficient.htm.

IX. APPENDIX

Full Budget Sheet

Description	ASUP Fall	ASUP Spring	Club	NASA Grant	Totals
Club Shirts		$995			$995
Testing Trip (Utah) – Air BNB		$138			$138
Testing Trip (Utah) - Transportation mileage		$1,720			$1,720
Proof of Life Video				$800	$800
Camera lens rental		$140			$140
Club Meeting Food		$90			$90
Team trip to Oregon Dunes - Gas for UP Van				$125	$125
Supplies/ Equipment	$2,353	$1,009	$788	$4,050	$8,200
Stem Outreach workshop materials	$100	$120			$220
Total Budget	**$2,453**	**$5,000**	**$788**	**$4,975**	**$12,428**
Spent to date	$2,453	$2,988	$788	$800	$7,029