2017 SYSTEMS ENGINEERING PAPER

NYU Robotic Design Team

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Abstract

With the current goal of space exploration and colonization NASA has looked towards inhabiting our neighboring planet Mars. In order to be able to sustain human life on Mars and enable a return trip back to earth NASA has invested research into the concept of In-Situ Resource Utilization (ISRU), where resources found outside of the earth are used to complete the requirements of a space mission. To be able to conduct ISRU operations, NASA has proposed the use of robotic excavators to extract raw resources from other planets, such as Mars, and deliver them back to a processing unit for them to be converted into useful materials such as water, fuel, or building mediums.

To assist in the design and development of ISRU robotics, as well as engage college students in space and robotics activities, Kennedy Space Center KSC created and hosts the NASA Robotic Mining Competition, where college teams compete by traversing a simulated Martian terrain, excavating BP-1, and returning it to a collector bin, similar tasks to the mission that NASA wishes to be carried out by an ISRU mining robot. This competition invites students from different universities to compete in an engineering challenge and employ the methods of system engineering to accomplish the tasks defined by the competition.

This system engineering report describes the iterative design process the New York University Robotic Design Team (RDT) used to develop the Martian excavation rover built for the 2017 NASA Robotic Mining Competition (RMC). This paper illustrates the design, prototyping, redesign, assembly, and project management process RDT used to create the Atlas 07 rover.

1. Pre-Phase A Concept Studies

1.1 Mission Objectives

The objectives for NYU Robotics Design team are to design and create a simplistic, rugged and lightweight robot capable of performing well in the NASA Robotic Mining Competition. As an extra goal, the team is aiming for the robot to be capable of autonomous if not partial autonomous function.

1.2 Competition Requirements

The competition requires that the rover built adheres to specific requirements. The complete competition requirements can be found in the NASA RMC Rules and Rubrics on the competition website. The general parameters for rover functionality are listed in *Table 1*:

Competition Requirements
Excavate, Transport, and Deposit 10 kg of soil
Dimensions at start within 1.5 x 0.75 x 0.75 m
Weight shall not exceed 80 kg
Wireless teleoperation or autonomous control
Under 5000 kb/s bandwidth consumption
Traverse arena and complete task in 10 minutes

Table 1: Competition Requirements

1.3 Robot Organizational Structure

The team and robot organizational structure (*figure 1*) was split into four main disciplines: Electrical, Mechanical, Software, and Autonomy. While each sub-discipline closely interacted with the other disciplines this organization was used to organize tasks.

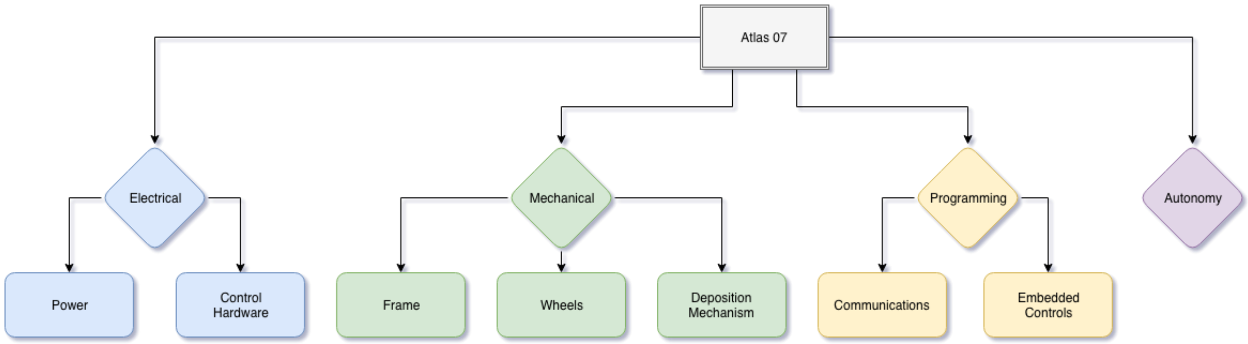


Figure 1: Team Organizational Structure

Autonomy was kept as its own sub-team to reduce the risk of the entire project failing if deadlines with autonomy were not kept. Due to the difficulty of autonomy and limited resources, autonomy was kept as an optional "reach" goal. The robot was then designed to be compatible for autonomous operation.

2. Phase A: Concept Technology

2.1 Original Concept

The development of the rover stemmed from the design of a previous rover Atlas 06 (*figure 2*), that was intended to debut in the 2016 RMC challenge. Atlas 06 featured a very lightweight design featuring a skeletal frame, minimalistic digging wheels, and a deposition mechanism.

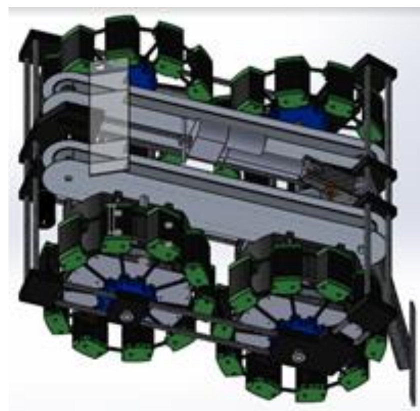


Figure 2: Atlas 06

2.1.1 Mechanical

There were several reasons why the construction was not completed for the competition, including unforeseen complications that increased the complexity of the design, failures in the design's ability to hold and deposit BP-1, and issues with the structural integrity of the robot itself.

2.1.1.1 Atlas 06 Frame

The frame of Atlas 06 (*figure 3*) was designed to be extremely lightweight, comprised of carbon fiber rods and 3D printed linkages. Theoretically, this frame would be easy to assemble, disassemble, and be redesigned/repaired easily until the final stages of construction. Once the entire rover was assembled, the carbon fiber rods would be epoxied into the plastic blocks, creating a rigid frame.

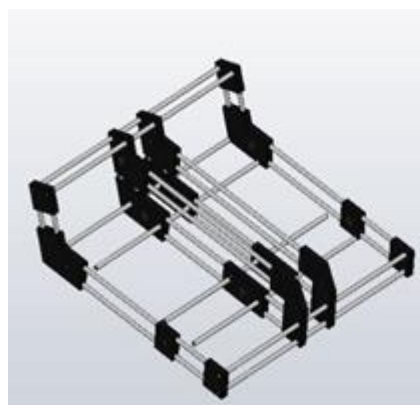


Figure 3: Atlas 06 Frame

2.1.1.2 Atlas 06 Wheels and Digging

The design of the wheels (*figure 4*) reflected the overall design philosophy of Atlas 06 to be extremely lightweight and modular. By combining the driving and excavation mechanisms the total rover weight was reduced. The wheels of Atlas 06 were made of individual 3D printed shovels linked together to form a circle. A single wheel consisted of ten 3-D printed shovels, a 3-D printed central hub, and plastic connectors. The central hub was connected radially to each shovel by a thin, round plastic linkage. However, the design was ultimately deemed too weak to perform the tasks required by the competition.

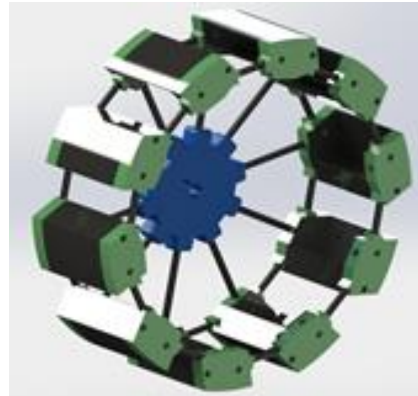


Figure 4: Atlas 06 Wheel

2.1.1.3 Atlas 06 Deposition Mechanism

The deposition mechanism (*figure* 5) was the most complex system in the entire Atlas 06 system, and the heaviest. The BP-1 dug by the wheels would fall into collecting bins held within the robot's chassis. A linear actuator with a carbon fiber rod were then used to make the robot stand up next to the collector bin, giving the robot the height required to deposit the stored BP-1 into the collector bin. A 90° gearbox motor would then run two belts that would take the BP-1 up to a deposition plate, made of thin aluminum sheet, set at an angle, which would fall into the bin

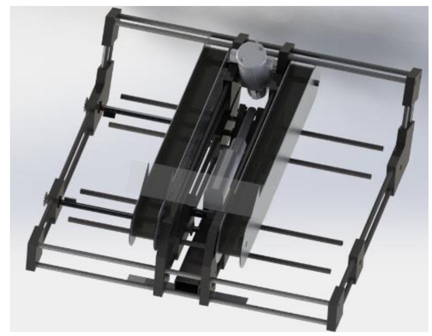


Figure 5: Atlas 06 Deposition Mechanism

2.1.1.4 Drivetrain

Atlas 06 used a chain drive system with a single motor on a gearbox providing power to one side of the robot. While this system reduced weight by eliminating extra motors, gearboxes, and motor controllers, it greatly increased the difficulty of assembly and introduced internal torque on the chassis.

2.1.2 Electrical

Atlas 06 featured a failsafe relay system which allowed the robot to continue functioning even if the voltage current sensor was damaged. The main controlling switch is the double pull double throw relay (DPDT), which allowed the system to be powered on or off in multiple states. The battery would supply power through the voltage current sensor, a DPDT common 2, and the main switches to the relay. When all switches are on, the robot will be powered as the electronics are connected to the common 1. In the case that the voltage current sensor breaks from over currenting, there is a NMOS to cut power into the relay, causing the DPDT switch to enter off state, which still allows power for the robot for emergency driving. This circuit connection became too complex and bulky, thus was not used for future robots.

The entire electrical board was aimed to be printed onto a single circuit board, then wired to components to simplify connections. All microprocessor, h-bridges, and regulators were to be connected to headers that are soldered on. The connections to the motor controllers became difficult, as there were no dedicated pads for the controller connections. It was found that these printed boards had issues with handling heating from high current draws, along with linear regulators being unable to handle the currents pulled.

2.1.3 Controls

Atlas 06 was controlled by a single micro controller that was teleoperated using a "WiFly" module compliant with the 802.11 waveform required for the competition. Commands were received from a ground station which transmitted the commands via a LabView interface. In order to build a more efficient and easy to understand system, the team decided to change to using Python sockets to build a new communication system. The idea was to use a network socket to communicate with the WiFly and the ground control station while maintaining a secured connection. A good internet protocol suite to use would be the TCP (Transmission Control Protocol) as it handles secured connection with its three-way handshake.

2.2 System Requirements

Many advantages present in Atlas 06's design led the team to conclude that it was a baseline concept that could be improved to become a viable competitor in the 2017 RMC. Issues with the design were researched and addressed, such as the structural weakness in the wheels, the infeasible design of the deposition mechanism which was heavy and ineffective in carrying BP-1 from the internal bin, and the drivetrain system being difficult to assemble.

2.2.1 Mechanical Requirements

- The robot shall weigh no more than 35 kilograms at its unloaded, starting configuration
- The robot shall be able to dig at minimum 10 kilograms of BP-1 per traversal of the field
- The robot shall be capable of filling the bin to 10 kilograms of BP-1 within at most 20 seconds of operation in the digging area
- The robot shall be able to lift all dug BP-1 to the necessary height of 0.60 meters above the ground, accounting for unevenness of the terrain.
- The robot will be able to dump 10 kilograms of BP-1 into the bin within 5 seconds
- The robot should be able to move forward at least at a speed of 2 meters per second when unloaded and at least at 1.5 meters per second when loaded
- The robot shall have mechanical sealing for its electrical components for dust tolerance

2.2.2 Power Requirements

- The robot shall run on a single 24V battery
- Robot shall have voltage regulation for generating 5V, 9V and 12V for different usage
- The robot shall report back how much power has been consumed
- The robot shall provide protection against short circuit
- The robot shall electronically isolate the components to avoid any accidental damage
- The robot shall have a prominent E-stop switch
- Robot shall not draw more than 60 amps

2.2.3 Control Requirements

- The robot shall be controlled by a joystick from the ground station
- Robot communicates only in an internet protocol
- Static IP is set for WiFly so it does not change mid-competition
- Average bandwidth has to be under 5000 kbits/sec
- All robot operations come to a halt when connection is lost with the ground station
- Robot will reconnect if connection is lost with ground-station

2.2.4 Autonomy Requirements

- The robot shall not use walls as reference to determine current location or desired direction
- The robot shall map most part of the field in initialization
- The robot shall avoid all rocks in the trajectory
- AprilTag detection range shall be larger or equal to 7 meters
- The robot shall use AprilTag as reference to moving back and forth between the collect bin and mining area

2.3 Mission Concept

The robot will operate in accordance with the following:

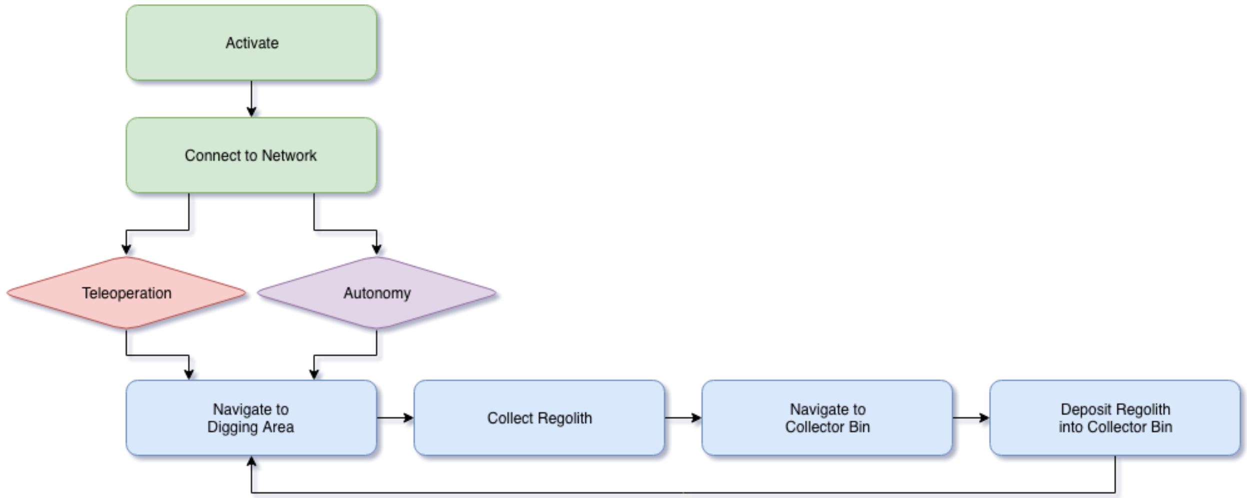


Figure 6: Mission Concept

3. Phase B: Preliminary design

The design of Atlas 06 was completely analyzed for pros and cons, and the first new design iteration Atlas 07β was developed. The initial budget can be found in Appendix B. The development is described for each of the components.

3.1 Mechanical

3.1.1 Atlas 07β Frame

Figure 7: Atlas 07 β

For the Atlas 07β frame, the Atlas 06 frame was lengthened from 27.6 inches to 40.34 inches to allow for the installation of larger wheels, a scissor lift bin system and its associated linear actuator, and the addition of a discrete electrical box. The strength and stability of the frame was increased by adding a central 3D printed structure, (*figure 7*), partially to reduce the torsional stress that the previous frame experienced (which caused cracking in the plastic linkages), and to account for the larger volume and weight of the lengthened frame. The frame was designed to secure via set screws, instead of glue, allowing for ease of frame assembly (and disassembly). However, it was noted that one set screw would not be enough to hold a carbon fiber rod, so multiple were required per plastic linkage and carbon fiber rod.

3.1.2 Atlas 07β Wheel Design

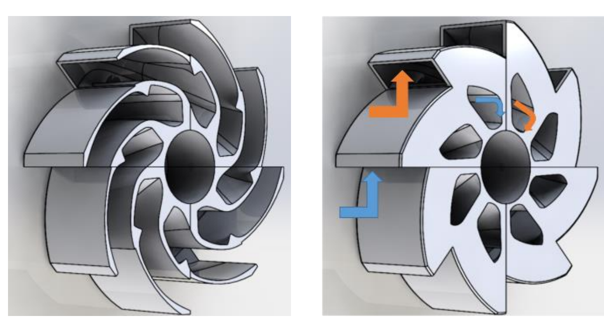


Figure 8: Atlas 07β Wheel

Since the Atlas 06 wheel design was not robust enough for the digging and driving tasks, a solid and enclosed wheel design was developed with inspiration from a previous design. Improvements included increased rigidity, control over volumetric flow intake, and less rolling resistance. The rigidity of the wheel comes from a glued together structural design comprised of multiple partially hollow sections of wheel (*figure 8*).

After considering six, eight, and ten teeth, an eight-tooth design was determined as the best way to maximize BP-1 intake. With six teeth, the intake area would be larger, but not all of the intake would be used. With ten teeth, the intake would be too small to collect larger materials and might be prone to jamming. The eight-tooth design determined the arc lengths and angles of the outer curves. The exit shape also had to be designed to match the intake volume and ensure that the BP-1 would fall at the highest possible point relative to the deposition mechanism.

3D printing was used because of the unique shape of the wheel, yet it presented several manufacturing challenges. The full wheel dimensions exceeded the capacity of available 3D printers, so it had to be printed as four separate parts. A light printing infill was used to reduce printing time and weight. It was determined that acetone welding would be used to bond the four wheels.

3.1.3 Atlas 07β Deposition Mechanism

When designing the new chassis, a new deposition mechanism was designed. Learning from the mistakes made with ATLAS 06, it was unanimously decided that the mechanism should be simple and feasible.

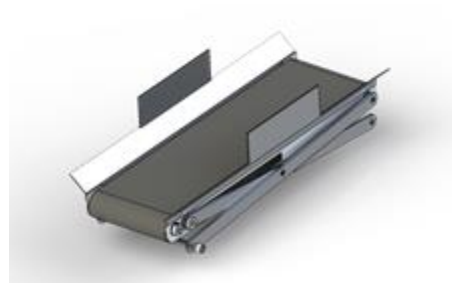


Figure 9: Atlas 07β Deposition Mechanism

The final design considered for the deposition mechanism was a scissor lift. BP-1 exiting the wheels would go on the ramps leading to the bin. When at least 10 kg of the BP-1 is collected into the bin, the scissor lift system would lift the dumping system and dump the BP-1 by turning the conveyor belt. The belt is able to propel the excavated BP-1 into the collector bin. This design is not the lightest, but the tradeoff is that the deposition mechanism is now easier to construct and it can collect more BP-1 than previous design iterations.

3.2 Electrical

The focus of both Atlas 07 and Atlas 06 electrical system was modularity, reusability, ease of use, and troubleshooting. To achieve these goals, custom PCBs would be designed and implemented onto the rover.

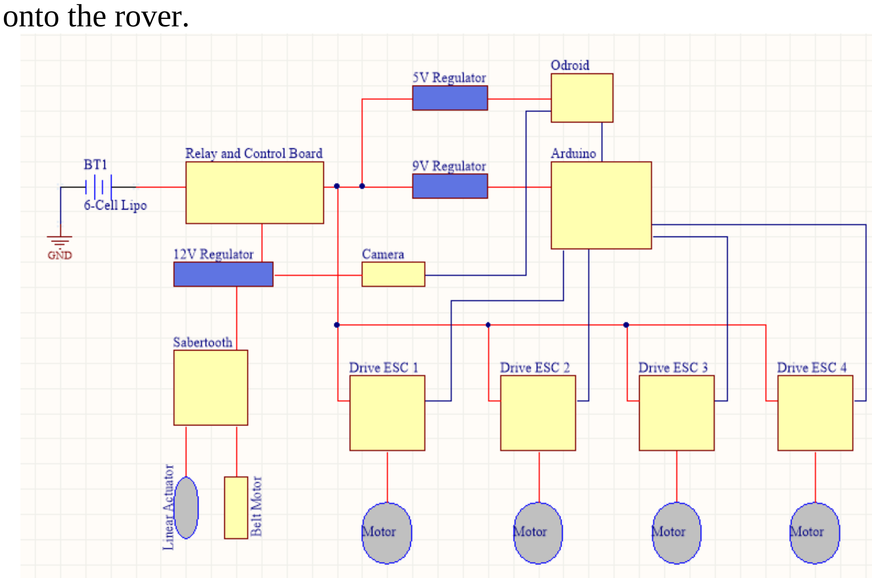


Figure 10: High-level Circuit Diagram

3.2.1 Power Distribution

The power distribution requirements were initially met by using a 24V battery. To power other components rated for lower voltage, voltage regulators were designed. A voltage current sensor was used to record the amount of power consumed which was reported on an LCD screen. In this case, battery selection became a major decision that was weighed against all options. To provide enough power to the robot for a 10 minute run, power calculations were done. These calculations took a factor of safety into consideration. After calculating nominal current loads for all high-powered devices, the estimated energy consumption came out to be around 181.8 Whr. This calculation takes into consideration operating the robot under this load continuously for double the time needed. The battery was a commercial off the shelf (COTS) item chosen based on a trusted vendor as well as its dimensions for the requirements needed to satisfy the energy needs. A 6 cell, 9Ah LiPo was chosen from MaxAmps since it has a 100C rating and is able to provide almost double the energy needed even with a factor of safety accounted for.

Energy Consumption								
Type	Function	Component	#	Voltage	Continuous Current (A)	Power (W)	Time (min)	Total Energy Consumed over time (Whr)
Drive	ESC for Brushless Motors	RoboteQ SBL1360	4	24	4	96	20	32*4
Pulley	Motor Controller	Sabertooth 2x25 V2	1	12	10	120	10	20
	Sensor	AttoPilot Voltage and Current Sense 180 A	1			4	20	1.3
	Microprocessor	ODROID XU4	1	5	4	20	20	6.7
	Microprocessor	Arduino Mega	1	5	1	5	20	1.7
	Communication	WiFly	1	3.3	0.12	0.396	20	0.2
Autonomy	Sensor	RPLidar A2	1	5	0.45	2.2	20	0.71
	Sensor	Camera	1	5	2		20	3.33
Total								181.8

Battery								
				Battery Voltage	Continuous Current (A)	Power (W)	Time (min)	Total energy supply for time (Whr)
	Power supply	LiPo 9000XL 6S 22.2v	1	22.2	9	198	20	198

Table 2: Power Distribution

3.3 Software

3.3.1 Embedded Controls

A micro controller was used to handle low level commands for the robot including actuation controls such as the motor controllers. An embedded microprocessor was preferred over a Single Board computer (SBC) because a micro controller reacts in real time and is not hindered by other operations called by an operating system.

3.3.2 Networking and Communication

Originally, the idea was to use TCP (Transmission Control Protocol) to communicate with WiFly and the Arduino Mega. Because of the three-way handshake that the python TCP socket already has, the system seemed to be stable at the cost of more bandwidth. However, the team then decided to use a customized UDP (User Datagram Protocol) system. The customization will feature a connection status in the protocol as a way to imitate the TCP three-way handshake while offering less bandwidth usage. In addition, the team plans to design a control protocol for expansibility and systemic consideration.

The communication system takes inputs from a joystick controller that are encapsulated into a customized UDP packet from the ground station (GCS) laptop. The input packets are then sent through the router connected with the LAN connection to a Wifly connected to a micro controller. The microcontroller will then decode the packet into commands that the robot will perform.

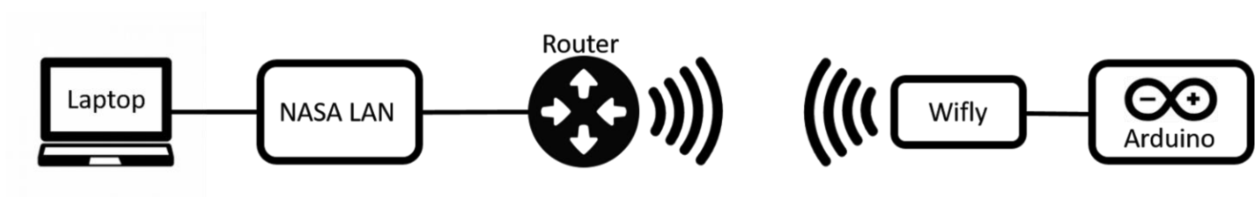


Figure 11: Network Diagram

3.3.3 Autonomy

To test out the concept for the robot, a simulation using ROS and Gazebo was created. The environment of Mars was simulated, with Atlas and the LiDAR navigating throughout. Within the simulation system, Atlas is able to run in two modes: manual and automatic. While running manually, the direction and speed can be controlled by keyboard; in the automatic mode, Atlas can navigate itself to an assigned location while mapping the obstacles based upon distance.

RPLIDAR A2, a 360-degree 2D LiDAR, is used to detect obstacles at a range of 0.15 to 0.6 meters, with a sampling frequency of 4000 Hz. The Hector SLAM algorithm was used to test the performance of the LiDAR. A Raspberry Pi 3 Model B was used as the microprocessor during testing, but the computation speed was proven to be unacceptable when running the SLAM algorithm, drawing the map, and navigating the robot.

4. Phase C: Final Design and Fabrication

The Atlas 07β rover was analyzed for its achievement of the competition requirements and for potential failures. This design review led to the development of the final design. The revision of each component is described for each subsystem. The weight analysis of the mechanical design is shown in Appendix A.

4.1 Mechanical

4.1.1 Finalized Frame

The major change between the Atlas 07β frame and the Atlas 07 frame is the relocation of the electrical box and the bin. The initial design for the bin which was to place it in the middle of the rover failed to work since the end of the bin could not reach over the frame. When the robot was depositing, it had to touch against the wall. If the pulley could not create enough forward momentum for the regolith to fall towards the collector bin, regolith would fall on the robot. Therefore, the bin system was moved to the front of the frame and the electrical box to the back.

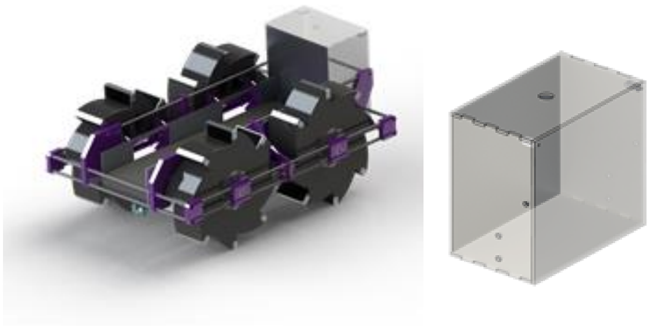


Figure 12: Atlas 07 Final Design

To secure the functionality of the electrical system and minimize the disturbance from the surrounding environment, it was crucial to build an isolated container that separates the electrical system from the rest of the systems. It also needs an easy access for maintenance and modification. Critical characteristics of the electrical box are dust-tolerance and heat-dissipation. Dust-tolerance requires a good mechanical sealing performance. All the narrow apertures between the connections are possible entrance for the regolith dust.

The electrical box is made of ¼ inch acrylic sheet except for the ¼ inch aluminum back plate, which acts as a heat sink. The backboard and four sides are glued in place and the front cover is designed to be connected via screws. The box can effectively prevent the dust from contaminating the electrical components by using rubber around the opening. The electrical box is a critical interface between electrical system and mechanical system.

4.1.2 Finalized Wheel

Using SOLIDWORKS, Atlas 07 wheels were tested and BP-1 was used on small scale 3D printed models to decide the best shape for the wheel to allow the BP-1 to smoothly flow out of. Acetone welding was the joining method of choice as in Atlas 07β. First, spare ABS plastic parts were dissolved in liquid acetone. The thick solution was then applied on all connecting edges of the wheels and pressure was applied with clamps. The method was the best because the connection was very strong and the curing time was less than 24 hours.

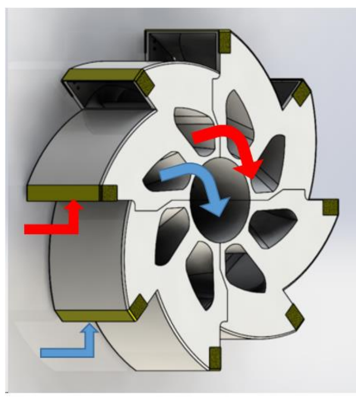


Figure 13: Atlas 07 Wheel

4.1.3 Finalized Deposition Mechanism

The most difficult part of the deposition mechanism was to transport the regolith from the wheel to the bin; a 3D-printed part was designed to facilitate regolith transfer. One problem was the position of the wheels and bin limited the plastic connection to be at most at a 25° angle. This angle was not sufficient to let BP-1 flow freely in a static environment, so it was decided to add a small cell vibrator motor inside each plastic piece to help the regolith fall into the bin.

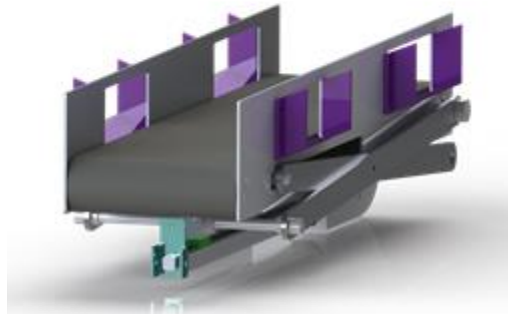


Figure 14: Atlas 07 Deposition Mechanism

Another issue that was brought up was the tiny distance between the transporter and the bin. It was predicted that a significant amount of regolith would fall out in that distance. A Silicone sheet was attached that the plastic piece, and will extend on top of the bin. When the regolith flows, it will fall near the center of the bin. The Silicone sheet is bendable so when the bin is lifted it will bend and allow the bin to rise.

The bin is made from aluminum sheet metal. The sheet metal was cut by a water jet cutter. Height and width limits of the water jet cutter bed caused the bin to be cut into several pieces. The pieces were then epoxied together and connected by steel L-brackets. Making the bin out of metal makes it heavy but it is a tradeoff worth making, as it gives the bin more structural integrity and allows for more regolith to be collected during each run.

4.2 Electrical

4.2.1 Power

Atlas 07's main electrical switch is an 80 ampere-rated relay. The relay power coil is connected to an emergency switch, secondary mechanical switch, and a protection circuit board. The switches in series to the coil allows any of the protection switches to turn off Atlas 07, while requiring all of them to be engaged to activate Atlas 07. The relay coil is powered by a custom protection circuit. The circuit comprises of a BJT, a diode and linear regulator rated for 5V to bias the BJT. A diode is connected parallel to the coil of the relay with the anode of the diode connected to the 24V supply and the cathode of the diode connected to the collector of the diode. When the main switch and the emergency switch are engaged, 5V is supplied to the base of the BJT thus making the BJT enter saturation mode, this indeed connects the collector and the emitter of the BJT that is GND is connected to the cathode of the diode, a potential difference is produced across the coil of the relay thus energizing the relay. The high impedance in the bipolar junction transistor protects the coil from drawing greater current than it is rated for, and a diode prevents back EMF. This protection circuit can be seen in *figure 15*.

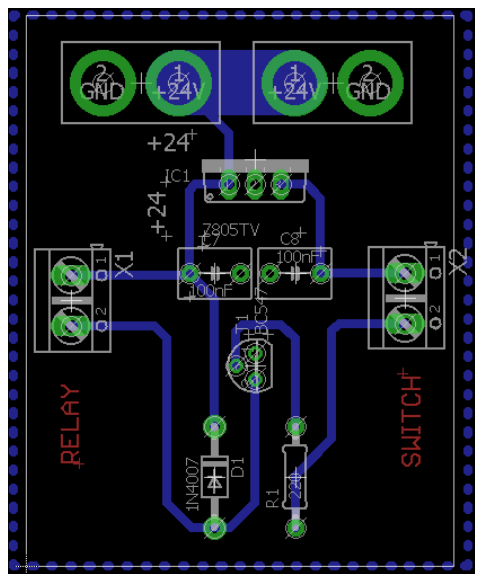


Figure 15: Main Relay Schematic

A commercial DC/DC 24-to-12 volts switching voltage regulator was chosen for its superior efficiency and onboard heatsink. This regulator was used to power the Sabertooth motor controller, and by extension the linear actuator and pulley motors. A commercial Polulu 5V regulator was used to power the Arduinos, Odroid microprocessors, and FPV camera. COTS solutions for voltage regulation were chosen after considering the drawbacks of in-house solutions; in-house solutions were generally larger and required difficult SMD soldering. Three busbars are present on Atlas 07 for voltage distribution: one at 24 volts, one at 5 volts, and one acting as ground. Busbars were chosen for their convenience in mounting and connection, providing a neater final product than individually joining circuits together.

4.2.2 Drive and Pickup Controls

Atlas 07 is driven by four brushless motors; one brushless motor is attached directly to each wheel. Each drive motor is controlled by an SBL1360 Brushless motor controller; the motor controllers are controlled via PWM signals from an Arduino Mega. Brushless motors were chosen for their lower current requirement, lighter weight, higher efficiency, and greater reliability. Additionally, they are capable of both higher speed and higher torque than brushed motors. Brushed motors, driven by a Sabertooth motor controller are more cost effective and are used to actuate the scissor lift and conveyor belt. The linear actuator was used to push the arm of the scissor lift horizontally to create vertical motion for the regolith conveyor belt.

4.3 Software

4.3.1 Embedded Controls

The embedded controller operated by interpreting commands provided to it by an opcode. The controller would interpret the opcode as an action the perform that action. A joystick is used to send x-axis and y-axis coordinate locations. The x-axis represents the left or right motion and the y-axis represents the forward and backward motion. The position of the joystick is translated into motor commands on the driver station computer. The command is then transmitted to the embedded controller on the robot which then integrates it with rest of the robot operations.

4.3.2 Network Communications

4.3.2.1 Heartbeat

The team introduced an innovative approach to minimize bandwidth usage and guarantee a reliable connection. The approach is called a Heartbeat system. The core concept of the Heartbeat system is to mimic a TCP protocol but with a more compact data structure. The system runs in specified refresh rate, the default being set at 30Hz. In every transmission, the GCS sends the request first. This request can be either a heartbeat packet or a packet carrying some updated data since the last non-heartbeat transmission. After the robot receives the packet, it parses packet, runs commands, and returns a heartbeat packet if the GCS the sent a heartbeat packet or did not request any data, or returns the requested data to GCS. System also has two fail counters in both GCS and robot, which will increase every transmission interval only if there is no transmission, and is set to zero once there is correct communication presenting. The transmission should be done every refresh interval, otherwise after transmission fail counters reach fail-safe threshold (10 default), GCS and robot will start fail-safe process to keep robot away from danger.

4.3.2.2 Customized UDP Packet

The team chose to create a customized UDP with a one byte flag that indicates the type of a data frame to be transmitted between the robot and the GCS. The customized UDP is very similar to the UDP packet with the exception of having the one byte flag to describe the packet and the content of the UDP payload field. There are three types of data frame packets: the heartbeat packet, the request from GCS packet, and the response from robot packet. Each of the data frame connections between robot and GCS are shown in *figure 16.*

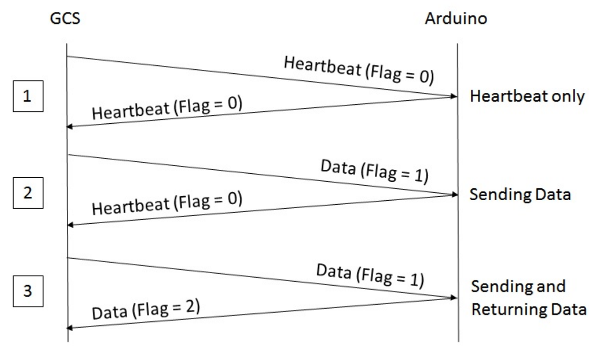
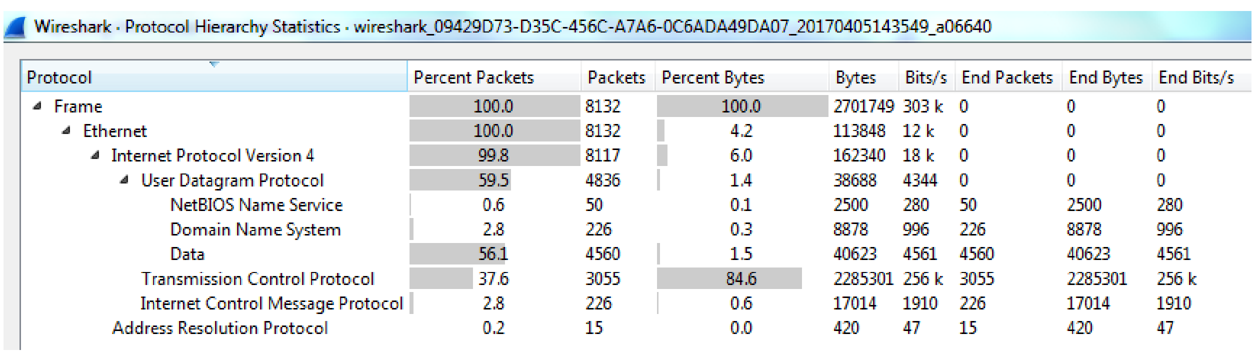


Figure 16: Client and server Data Transfer

The data frame header also contains the prefix field, the length field for the payload, and the payload field. The prefix field identifies the data frame as used only in the team's communication system and describes as the beginning of the data frame to avoid conflicting data in the payload field.

4.3.2.3 Design Margin

From the bandwidth testing using Wireshark module, the average bandwidth of the communication protocol was found to be 26 kbits/sec. The design is well under 50 kbits/sec even when overloaded with packets. When combined with the IP camera for first-person view, the bandwidth was found to be 303 kbits/sec. The camera bandwidth can be estimated to be around 270 kbits/sec at a very low bitrate with low resolution.



Wireshark · Protocol Hierarchy Statistics · wireshark_09429D73-D35C-456C-A7A6-0C6ADA49DA07_20170405143549_a06640

Protocol	Percent Packets	Packets	Percent Bytes	Bytes	Bits/s	End Packets	End Bytes	End Bits/s
Frame	100.0	8132	100.0	2701749	303 k	0	0	0
Ethernet	100.0	8132	4.2	113848	12 k	0	0	0
Internet Protocol Version 4	99.8	8117	6.0	162340	18 k	0	0	0
User Datagram Protocol	59.5	4836	1.4	38688	4344	0	0	0
NetBIOS Name Service	0.6	50	0.1	2500	280	50	2500	280
Domain Name System	2.8	226	0.3	8878	996	226	8878	996
Data	56.1	4560	1.5	40623	4561	4560	40623	4561
Transmission Control Protocol	37.6	3055	84.6	2285301	256 k	3055	2285301	256 k
Internet Control Message Protocol	2.8	226	0.6	17014	1910	226	17014	1910
Address Resolution Protocol	0.2	15	0.0	420	47	15	420	47

Figure 17: Average bandwidth of communication protocol and camera

4.4 Autonomy

The autonomy system for Atlas 07 is designed to use a LiDAR sensor and a USB camera to navigate the environment. The autonomy strategy can be summarized in three parts:

1. The Atlas 07 will use a USB camera to find AprilTag patterns and use them to orient the robot. The camera is mounted to the top of the rover on a rotating 360-degree gimbal, which can calculate the correct vector toward the drop/dig site destination.

2. When the Atlas 07 is going through the obstacle area, the RPLIDAR A2 will detect the obstacles and draw the map of the whole area in order to navigate the robot. Since the Atlas 07 has enough trafficability to go across craters, the only obstacles that Atlas 07 needs to avoid are rocks.

3. Once the Atlas arrives at the dig area, it switches to the digging process. The same strategy as mentioned in (1) & (2) will be used to return to the starting area after finishing digging. The Atlas will then repeat the strategy.

4.4.1 ROS and Simulation

The microprocessor used for Atlas is the ODROID XU4, running the operating system Ubuntu 14.04. This was more successful than the Raspberry Pi 3 due to the software framework of the control system is based on ROS (Robotic Operating System) Indigo, which is more reliable than the newest edition, ROS Kinetic.

4.4.2 LiDAR

The LiDAR will collect and send distance data to the ODROID. Then, the ODROID microprocessor will analyze the data and create the map of the obstacles on the field. The ODROID will communicate with the Arduino using the ROS Arduino bridge package, controlling the motor to make the robot move follow the directions to the desired location, from navigation based on AprilTag sensing, and avoid the obstacles.

4.4.3 AprilTags

Two different AprilTag targets will be placed onto the collection bin. By detecting the AprilTag target using the USB camera, Atlas 07 is able to determine the direction to move. The tags can be printed from an ordinary printer, and are easy to create and deploy. The AprilTag detection software uses the camera to detect the AprilTags in the video feed and calculate position and orientation based upon the identity of the tag.

5. Phase D: System Assembly, Integration, and Test

5.1 Testing

The rover was initially tested for driving capabilities. The first tests occurred on a carpet floor. During these tests three major issues were realized. The strength of the acetone weld was insufficient, the key stock connection was not strong enough for the applied torque, the aluminum drive shaft was not strong enough. As a result of these issues, the wheel and the aluminum drive shaft broke. This made it necessary to redesign the connection between the motors and the wheels.

Testing was further conducted on the linear actuator under the scissor lift. The original actuator was capable of outputting 35 pounds of force and when attempting to lift an unladen scissor lift, the system worked effectively. When laden with 10 kilograms of weight, however, the scissor lift failed. It was found that the starting angle of the linear actuator was too low for the effective output force being applied to it. To resolve this issue, the team agreed to upgrade to a 900 pound force actuator and resolved to use a starting angle of 5° from the vertical plane for the lift.
The communication system was tested to make sure the WiFly attempts to reconnect upon loss of connection to the driver station. Each motor of the robot was stress-tested to determine the maximum current it can draw since the documentations usually either overshoot or undershoot the realistic value. The total value was taken into account to double-check the current rating for the key components: the relay. In order to avoid any damage by short-circuit, a circuit breaker was added to the robot at this phase.

5.2 Repairs

The first repair occurred due to a break in the initial testing. A new full infill hub with a longer key slot was created, and each of the wheels was reprinted (adding over 200 hours of printing to our build time). The aluminum shaft that was used to connect the motor and the key cracked. The diameter of the motor D shaft was ¼ in, and the shaft was ½ in. Making a hole half of that diameter we should have noticed would break. It was replaced with a ¾ in steel shaft. The fix for this was modifying the wheels to add printing puzzle pieces that would fit together in each quarter and reprinting the wheels that had already been printed. After printing the new wheels, each of the four wheels were acetone welded together and then attached to the robot.

6. Phase-E Operations and Sustainment

6.1 Reliability and Risk

The following Risk Analysis Chart defines how the rover may malfunction and the severity of it:

	Cracked 3D printed part	Short Circuit	Multiple 3D printed parts cracked	
	Failure of Odroid	Overheating	Failure of Arduino	
Dust in the system			Too much current draw	Relay Latching to one configuration
		Failure of Odroid	Battery Low Voltage	

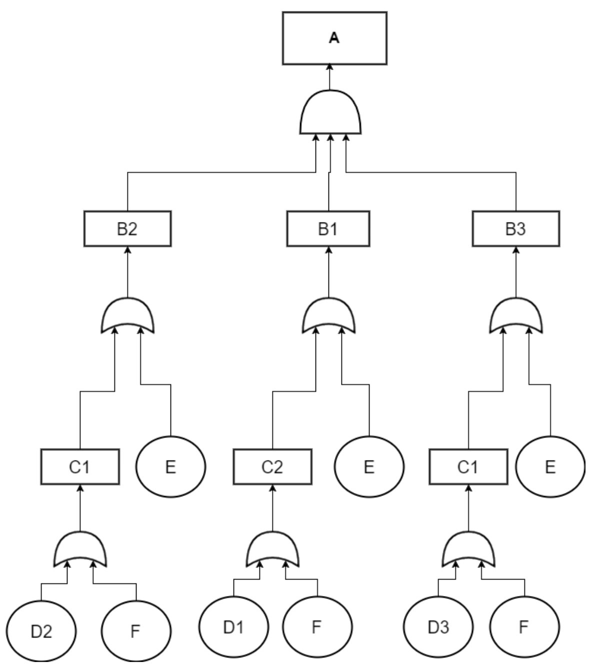
Figure 18: Risk Analysis Chart

Legend:
Low Risk (Green): These events do not disrupt the functionality of the rover and do not damage any of the parts of the rover. The damage caused by this event is minimal to negligible.
Medium Risk (Yellow): These events may disrupt the functionality of the robot. One event alone will not cause the entire rover to shut down, but the damage might cause the rover to not perform at its full potential. Part of the robot may be dysfunctional
High Risk (Red): These are the events that can halt the rover's operation entirely. The robot is not able to retrieve itself from this mishap mid-match and is rendered dead-weight in the arena.

Possible Mishaps	Pre-match Risk Mitigation
Wires connected incorrectly	Testing and checking the circuit
Bad soldering	
Hall effects sensors incorrectly connected	
JST connector comes loose	
Bugs in code	
Short circuit	
Relay coil-contact stuck open	
Relay coil- is dirty or pitted contacts	
Voltage regulator doesn't step down voltage	
Sand getting in the system	Electrical box

Too much current draw	- The motor controllers have built-in current protection -90 A rated Circuit-breaker will open in case of damaging current surge
Overheating	Heat sink, correct wire gauges
Wifly disconnected from the IP address	Wifly is set to reconnect as per the communication system
Motor controller-overcurrent	Protection on motor controller
Motor controller-under voltage	
Battery dies mid-match	Make sure battery is charged before match

Table 3: Electrical Risk Management



A	Robot Halts Operation
B1	All four wheels stop functioning
B2	Scissor lift Mechanism stops functioning
B3	Deposition Pulley stops functioning
B4	LiDAR dies in initialization
C1	Brushed Motorcontroller failure
C2	Brushless Motorcontroller failure
D1	Stalled Drive Motor
D2	Stalled Linear actuator
D3	Stalled Pulley Motor
E	Overcurrent
F	Wire Disconnection
G	Short Circuit

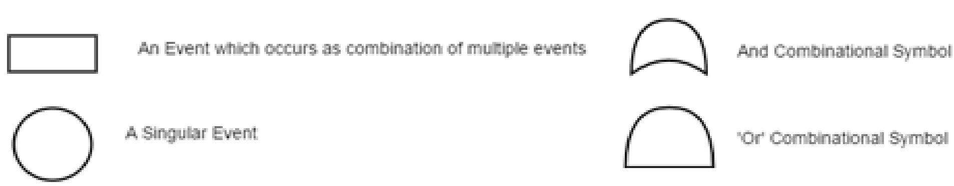


Figure 19: Failure Flow Chart

6.2 Trade-offs

Choice made	Old decision	Advantage	Disadvantage
Four brushless motors are used as the main four-wheel drive system for Atlas 07.	Could have used four DC motors	Brushless are efficient, have higher torque, much lighter, internal feedback and compact	Costs more, harder to code, requires more physical wiring
C-O-F regulators were used to step down voltages from 24 to 12,9,5V	Original plan was to find schematics online and print + solder boards ourselves.	Smaller, lighter, faster to obtain	Costs more, slightly less efficient, less skill required
Using a clear acrylic electrical box to contain all the electrical components	Using separate plastic containers	Able to observe the entire system, easier to move and remove components, allows heatsinking and prevents foreign matter from entering	Cost more, weighs more, requires more space
Using busbars	Direct soldering or wiring	Same source wiring, less complexity, easier to remove	Requires space, adds weight, higher exposure
Using a DPST switch, with the relay controlled by switches	The DPDT complex circuit, which allowed power if the sensor broke	Less complex, smaller.	Unable to run if components break
Three microprocessors	Single Arduino	Allows for autonomy, camera monitoring, current sensing, robot movement, and communications	Requires more power, wires, and cross communication
Using Odroid as microprocessor for autonomy decision	Using Raspberry Pi	More powerful in handling data	Consume more energy
Kinect is used for image capture	IP Camera	Images are more convenient to process	Shorter range and less angle of view

Table 4: Electrical Tradeoff Assessment

6.3 Interfaces

Since 60% of the robot is 3D printed the interface between the 3D printed parts and metal parts played crucial role in the build of the robot. Each wheel is comprised of four 3D printed parts which are fit together by means of Acetone Welding. Each wheel is connected to a brushless motor via a Steel shaft which are held together by means of set screws. The carbon fiber rods which formulate the structure of the robot are held together by 3D printed connectors. The rods and the connectors are secured by means of set screws.

Each of the Brushless Motors connect to the motor controllers via 14 gauge wires which provide the motors with proper sinusoidal current. The motor controllers are controlled by PWM signals from the Arduino. Each motor also has a Hall effect sensor which connects to the motor controller via JST connector. The Brushed motor controller is controlled using Serial Signals from the Arduino. Each such motor controllers can control two brushed motors. Hence only one motor controller is used on the robot.

Mechanical to Mechanical		
Component1	Component2	Means of Interface
3D Printed Parts	3D Printed Parts	Acetone welding
3D Printed Parts	Aluminum	Screws, nuts and bolts
3D Printed Parts	Carbon Fiber Rod	Set Screws
Carbon Fiber Rod	Carbon Fiber Rod	3D Printed Connectors
Mechanical to Electrical		
Mechanical Component1	Electrical Component 2	Means of Interface
Wheel	Brushless Motor Shaft	Set Screws
Scissor lift	Linear Actuator	3D printed fixture
Pulley Belt	Brushed Motor	3D printed fixture
Electrical to Electrical		
Component1	Component2	Means of Interface
Battery	Relay Circuit	XT60 connector, 12-gauge wire
Relay Circuit	Voltage Current Sensor	XT60 connector, 12-gauge wire
Voltage Current Sensor	Brushless Motor Controller	24V Marine Bus Bar
Voltage Current Sensor	Brushed Motor Controller	24V Marine Bus Bar
Voltage Current Sensor	12V Regulator	24V Marine Bus Bar
12V Regulator	5V Regulator	12-gauge Wire
Brushless Motor	Brushless Motor Controller	14-gauge Wire, JST Connectors
Brushed Motor	Brushed Motor Controller	14-gauge Wire
Arduino	5V Regulator	Stranded Jumper Wire
Arduino	Brushless Motor Controller	Jumper Cable, PWM Signal
Arduino	Brushed Motor Controller	Jumper Cable, Serial Signal
Arduino	WiFly	Jumper Cable, Serial Signal

Table 5: Interfaces

7. Project Management

7.1 Management Structure

The team was organized with the following hierarchy: Captain, Mechanical Co-Captains, and Embedded Systems Captain. This small hierarchy was aimed at having each member of the team be a leader in their own way, with 28 people on the team there is room for people to explore distinct roles on different tasks. These 28 members range from freshman to graduate level students, and pairing newer and more advanced students created a culture of mentorship and learning within the team.

Every Sunday NYU RDT has a full body meeting. At these meetings, the captain would review what was expected from the previous week, each subgroup would discuss what they had worked on and accomplished, then the new goals for the upcoming week would be discussed. In addition, at the end of every meeting anyone who had done exceptional work was given recognition. These full team meetings aimed at making sure everyone on the team was aware of what their teammates are doing, making sure that members felt responsible to be able to show what they had done, and to generate team spirit throughout the year. During the week, members would work on tasks in small groups. This made the three allotted cubicles a place of constant activity throughout the week. All team documents were kept in a shared google drive, CAD files were shared in grabCAD and Google Drive, and code was stored in a private GitHub. All team meetings were recorded with minutes, so that if anyone missed the meeting they could still know what was going on. In the lab, there are whiteboards with task lists and important dates posted for the whole team to see and follow through.

7.2 Timeline

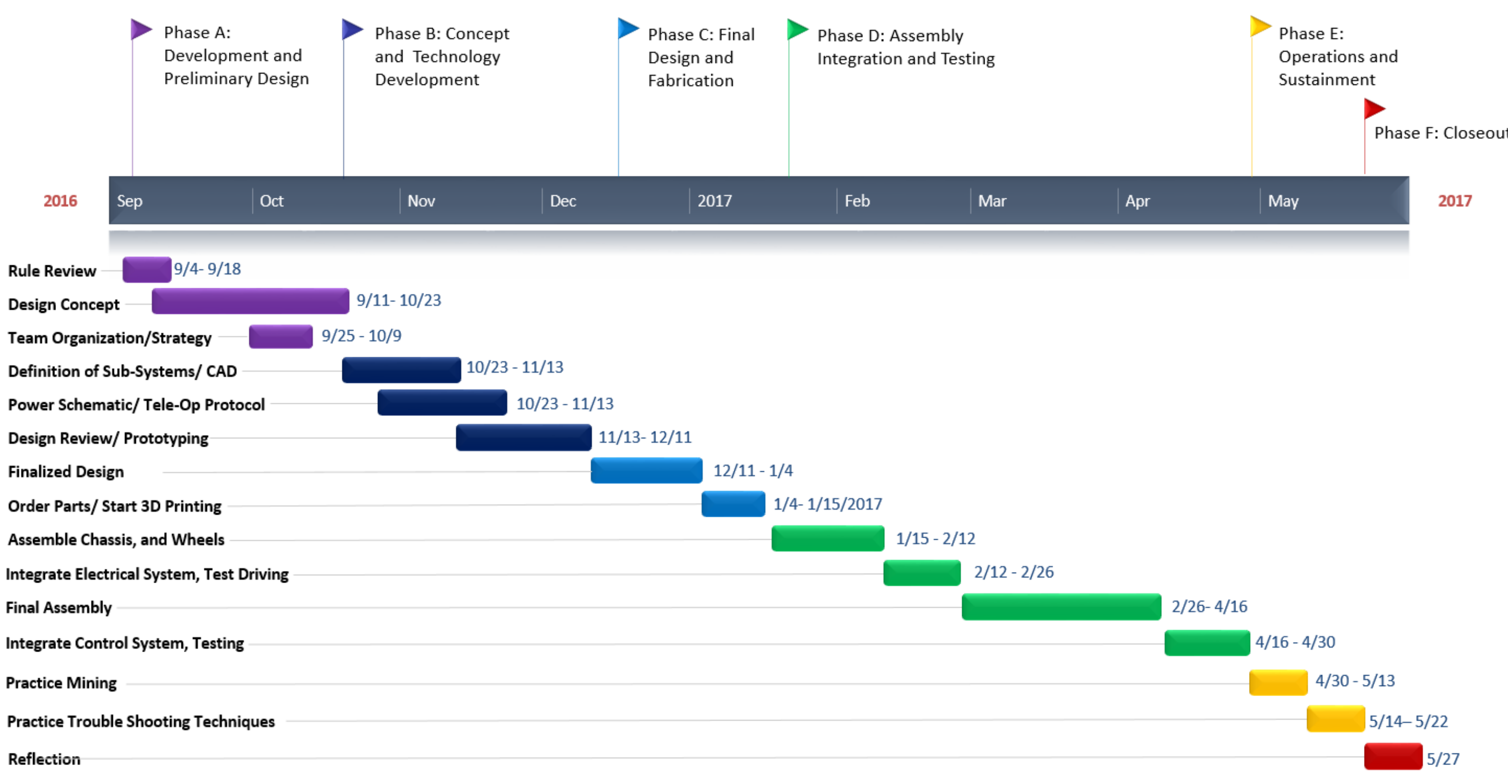


Figure 20: Systems Engineering Gant Chart

7.3 Financial Report

The NYU Robotic Design Team was fully funded through New York University. The Electrical and Computer Engineering Department, the Computer Science and Engineering Department, and the Dean's Office each contributed to this project. Dean Katepalli R. Sreenivasan and Dr. Haldun Hadimioglu from Tandon made personal contributions to the project. In addition, Mr. Jeffrey Lynford, a member of the Board of Trustees also made a personal contribution. The financial breakdown for the robot is shown in Appendix B.

8. Conclusion

This paper has outlined the systems engineering approach RDT used in the construction of the Atlas 07 rover. At the time of the systems engineering paper submission the rover was still undergoing testing. To the best of the team's knowledge the rover will perform to the outlined requirements, and each of the tested components described have been thus far reliable. RDT is excited to see what other teams have come up with for the 2017 NASA RMC challenge.

References

RMC, NASA, Official. *NASA's Eighth Annual Robotic Mining Competition May 22-26, 2017 Rules and Rubrics. Nasa.gov*. Web. <https://www.nasa.gov/sites/default/files/atoms/files/rmc2017_00_rulesrubrics_rev01_102617.pdf>.

Nasa Systems Engineering Handbook Pivirotto, Donna. *"The Nasa Systems Engineering Training Program." INCOSE International Symposium* 1.1 (1991): *NASA RMC*. NASA, 31 Dec. 2007. Web.

Appendices

Appendix A: Weight Budget

Part	Theoretical Weight (KG)	Actual Weight (KG)
Frame	6.6	7.6
Wheels	23.5	7.1
Collection System	4.8	5.0
Linear Actuator	3.5	3.5
Electrical components	4.9	5.3
TOTAL	41.4	28.5

Appendix B: Financial Budget

Projected Budget

Electrical Purchases	Quantity	Cost	Total
E-stop switch (Packet of Two)	1	$8.29	$8.29
XT-60	2	$8.99	$17.98
TSP40170 regulator	2	$3.88	$7.76
Deans connectors (x10)	1	$7.59	$7.59
CSD18501Q5A	2	$1.58	$3.16
CSD18531Q5A	2	$1.58	$3.16
LM2576T-5.0/NOPB-ND	2	$2.68	$5.36
LM2576T-3.3NS/NOPB-ND	2	$2.68	$5.36
PM2110-121K-RC	4	$2.37	$9.48
SR1045-TP	10	$0.65	$6.49
ESK107M035AE3AA	15	0.14	$2.10
35PK470MEFC10X12.5	10	$0.29	$2.89
BLWRPG173S-24V-4000-R91	2	$226.00	$452.00
Red Laser Pointer	1	19.95	19.95
Webcam	1	$66.28	$66.28
		Electrical Subtotal	**$617.85**
Mechanical Purchases	**Quantity**	**Cost**	**Total**
Gorilla Tape	1	$10.00	$10.00
3D Prints	50	$10.00	$500.00
Linear Actuator	1	$130.00	$130.00
Aluminum L angles	1	$35.00	$35.00
Aluminium Sheet	1	$76.00	$76.00
CF Rods	7	$42.00	$294.00
Set Screws- 10-32 Threading	1	$12.77	$12.77
Aluminium Bars (Dumping Mech Support	1	$34.80	$34.80
Needle Bearings	6	$12.00	$72.00
Ball Bearings	12	$6.00	$72.00
Timing Belt	4	$80.00	$320.00
Set screws	1	$5.00	$5.00
		Total	**$1,561.57**
Competition Travel Costs	**Quantity**	**Cost**	**Total**
Jet Blue Flight Round Trip ~ 200 +tax	20	$250.00	$5,000.00
Day's Inn Hotel Reservation 5 Rooms 6 Ni	1	$2,410.00	$2,675.10
Van Rentals: 2 (still figuring out)	2	$600	$1,200
		Travel Subtotal:	**$8,875.10**
Total Cost:			**$11,054.52**

Final Budget

Electrical Purchases	Quantity	Cost	Total
E-stop switch (Packet of Two)	1	$8.29	$8.29
XT-60	2	$8.99	$17.98
PWM Power Regulator	2	$3.88	$7.76
Deans connectors (x10)	1	$7.59	$7.59
Transistors	2	$1.58	$3.16
Transistors 2	2	$1.58	$3.16
Step Down Voltage Regulator	2	$2.68	$5.36
Step Down Voltage Regulator 2	2	$2.68	$5.36
Inductor	4	$2.37	$9.48
Diode	10	$0.65	$6.49
Acrylic Sheet 1/4 in	1	$94.01	$94.01
Capacitor	15	0.14	$2.10
Capacitor 2	10	$0.29	$2.89
Brushless Motor	2	$226.00	$452.00
Nextrox DC/DC Converter Regulator 24V Step Down to 12V 20A 240W	2	$18.00	$36.00
phr-5 jst connector	10	$2.00	$2.00
JST crimp connector, Part number: 455-2148-1-ND	20	$2.00	$2.00
Pololu 9V, 1A Step-Down Voltage Regulator D24V10F9	2	$7.49	$14.98
Pololu 5V, 2.5A Step-Down Voltage Regulator D24V22F5	2	$8.95	$17.90
Blue Sea Systems Common BusBars (100A-250A)	5	$9.00	$45.00
RadioShack Project enclosure Boxes	3	$11.50	$35.00
DC 24V 80A 5 Terminal SPDT Car Security Power Relay Socket	2	$8.00	$16.00
Stranded tin plated copper wire (300Vac, 25 feet, black)	1	$11.67	$11.67
BDPG-28-38-12V-4000-R139	1	$44.00	$44.00
Ip camera for first person view	1	$79.99	$79.99
		Subtotal	**$930.17**
Mechanical Purchases	**Quantity**	**Cost**	**Total**
3D Prints	50	$10.00	$500.00
Aluminum 3/16in thickness 1in x 2ft	1	$3.30	$3.30
Aluminum Bar 1/4in thickness 1.25in x 3ft	4	$7.76	$31.04
Aluminum Bar 3/4in thickness 2in x 3ft	1	$34.80	$34.80
Aluminum L angle 1/4in thickness 1in x 1in x8ft	1	$35.00	$35.00
Aluminum shaft 1/2in 12in	4	20.85	$83.40

Aluminum sheet 1/16in thickness 3/4in x 6ft	6	$3.78	$22.68
Aluminum sheet 1/8in thickness 4ft x 4ft	1	$285.00	$285.00
Ball Bearing 1/2in ID	4	$6.00	$24.00
Bushing 1/2in ID	2	$4.29	$8.58
Carbon Fiber Braided Rod 0.415in ODx4ft	7	$42.00	$294.00
Chain ANSI 25 5ft	1	$25.70	$25.70
Chain Connectors ANSI 25	10	$1.00	$10.00
Chain Sprocket ANSI 25 1/2in ID 14 teeth	2	$10.00	$20.00
M5 flathead screw 12mm pack of 100	1	$9.33	$9.33
M5 flathead screw 25mm pack of 100	1	$7.20	$7.20
M5 locknuts pack of 100	1	$5.98	$5.98
M5 nuts pack of 100	1	$5.55	$5.55
M5 roundhead screws 40mm	1	$9.86	$9.86
Metal Epoxy	2	$9.00	$18.00
Needle Bearing 1/2in ID	14	$12.00	$168.00
Set Screw 10-32 x 1/4in pack of 25	1	$11.00	$11.00
Set Screw 10-32 x 3/16in pack of 25	1	$12.75	$12.75
Shaft Collar 1/2in ID	10	$4.50	$45.00
Shaft Collar 3/4in ID	12	$4.92	$59.04
Silicone Rubber Sheet 1/8in thickness 1ft x 1ft	1	$17.95	$17.95
Steel shaft 3/4in 12in	2	$21.20	$42.40
Timing Belt H Series 2in width	4	$86.94	$347.76
		Subtotal	**$2,137.32**
		Total	**$3,067.49**