2015 RASC-AL Exploration Robo-Ops Student Challenge

Final Report

West Virginia University
Statler College of Engineering and Mineral Resources
The Mountaineers

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1 Introduction

The 2015 Revolution Aerospace Systems Concepts Academic Linkage (RASC-AL) Exploration Robo-Ops Competition serves to challenge collegiate teams in the design and development of a planetary rover at the Johnson Space Center (JSC) Rock Yard. This competition supports the NASA mission "to engage the public in its missions and research" by requiring teams to share updates via social media websites and performing outreach activities [1].

West Virginia University's (WVU) Mountaineer Robotics Team (MRT) has been working diligently since the previous competition to produce an improved rover for the Robo-Ops competition. The Mountaineers are confident they will be ready to perform in June at the 2015 Exploration Robo-Ops competition. The team is currently in the verification and validation stage.

WVU's new competition rover, the Mountaineer Mars Rover (MMR), had an initial requirement set by the team and advisor to improve certain aspects from the previous rover. This involved a complete chassis redesign and construction from a proven system. Goals included optimization of the chassis, modular design, assembly and disassembly, communications, and traction. This was achieved through the use of a split-chassis design, interchangeable drive system, improved antennas, and a variety of other modifications.

The MMR is composed of a mixture of different materials including aluminum, carbon fiber, and additive manufactured 3D printed parts. Previously the MRT had proven the usefulness of 3D printed parts for structurally important locations, but implemented it mainly for aesthetics with minor uses as brackets, support, and jigs to improve the workmanship of other components with the current design.

This report defines the system engineering process followed by the team, the development of the rover from requirements to fabrication, and the overall system design broken down into four major subsystems: drive, sample acquisition, control and communications (C^2), and the base station. The detailed technical specifications, mission plan, and public outreach activities are also included.

2 Systems Engineering

The MRT began the systems engineering process upon beginning class in the fall 2014 semester. The initial requirements analysis lead to the preliminary design presented in the proposal. The project kicked off upon reward of a competition spot and the development of the proposed design commenced began immediately. The necessitated implementation of an aggressive nineteen week schedule and a solid system engineering process to ensure completion by the end of the following semester. The systems engineering approach taken in based on the Capability Maturity Model Integration (CMMI) process-improvement model for product development [2]. The CMMI model is made up of twenty-two process areas covering the entire life-cycle of a product as well as organizational process improvement [2]. The entire CMMI model was not implemented, but select components were employed to ensure timely and successful completion of the project.

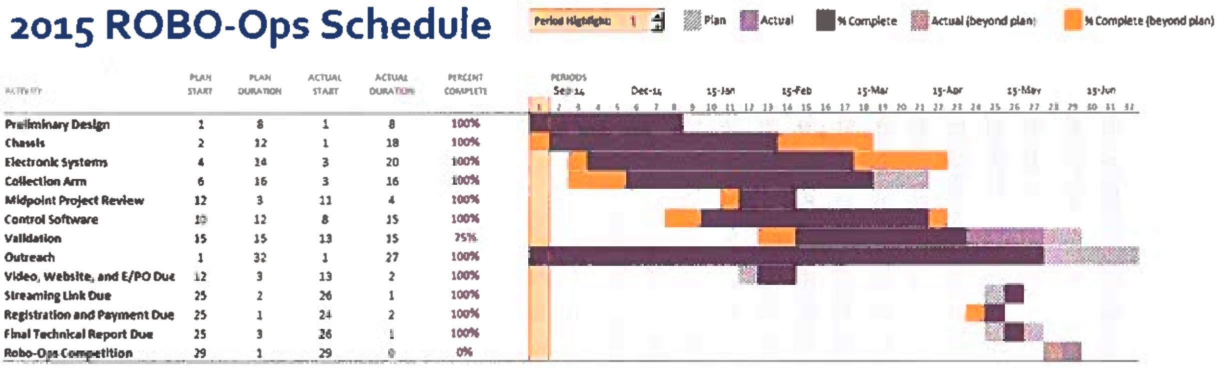
2.1 The Team

The project required the contributions of students spread across different engineering departments, and with different academic concentrations. This included graduate and undergraduate students spread between two courses and majors including: aerospace, computer, electrical, mechanical, and systems engineering as well as computer science. Coordination of the team necessitated development of a comprehensive project plan. Project planning increases overall quality and productivity through the estimation of work, determination or resources needed, production of a schedule, and identification and analysis of project risks [2]. Refer to the risk assessment matrix in the appendix.

The team's project plan details the project goals, deliverables, schedule, budget, risk mitigation, and team organization. The plan was developed per the *Project Planning* (PP) and *Project Management and Control* (PMC) process areas outlined by CMMI. The PP process area contains guidelines for establishing the basic components of a project plan including: project scope, schedule, budget, risk assessment, life cycle and team organization. The PMC process area provides guidelines for creating a project management plan through the definition of work products, or deliverables, that team management can use to track the project's progress.

2.2 Schedule

The team's schedule is shown below in Figure 1. The remaining schedule gives the team the ability to do further validation and testing prior to deployment at Johnson Space Center (JSC).



2015 ROBO-Ops Schedule

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Preliminary Design	1	8	1	8	100%
Chassis	2	12	1	18	100%
Electronic Systems	4	14	3	20	100%
Collection Arm	6	16	3	16	100%
Midpoint Project Review	12	3	11	4	100%
Control Software	10	12	8	15	100%
Validation	15	15	13	15	75%
Outreach	1	32	1	27	100%
Video, Website, and E/PO Due	12	3	13	2	100%
Streaming Link Due	25	2	26	1	100%
Registration and Payment Due	25	1	24	2	100%
Final Technical Report Due	25	3	26	1	100%
Robo-Ops Competition	29	1	29	0	0%

Figure 1 – Project Schedule Overview

2.3 Concept of Operations

The concept of operations describes the operator and system's progression during the mission to meet objectives. The mission objective of the rover is to traverse the simulated planetary surface at the JSC Rock Yard, find a collect rock specimens or targets, and return with them to the Mars Hill starting area [3]. A basic set of operations have been designed to assure these goals are met. The diagram in Figure 2 illustrates these.

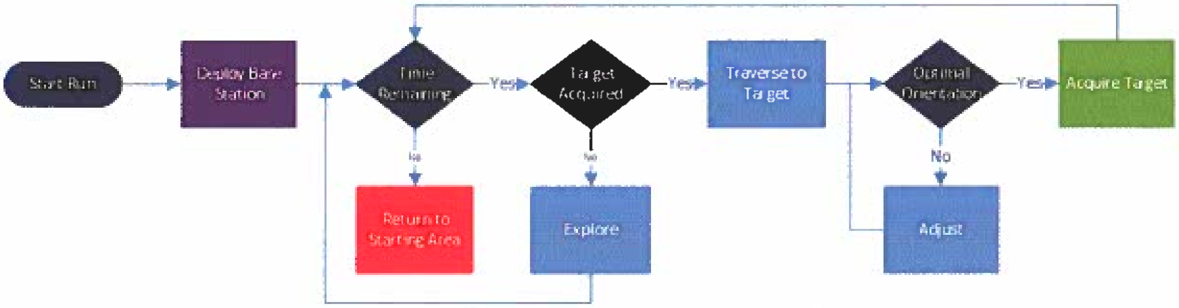


Figure 2 – Concept of Operations Flow Chart

2.4 Mission Control Operational Plan

Mission control will be staffed with a minimum team of two operators. The first will be the main operator or driver whose main goal is to maintain a known orientation and location on the map while keeping a steady pace through each area to ensure timing requirements are met. The second will be the co-operator or arm control expert who will be in charge of advising the driver on optimal orientation for rock collection as well as efficient collection of targets and scouting. Any additional members will assume the role of assisting the operators with their duties and providing moral support. All members will be present for the entire competition to ensure that rock locations from previous runs are noted and the strategy reviewed to maximize scores.

The driver reserves the right to be the final say in any decision making that needs to occur. Should a contingency to the plan occur, the assistants and co-operator will state any opinions before the decision is made. Any issues that could occur have been noted and discussed as a team during meetings and recorded with the optimal solutions. These are all available on the mission control computer. Practice runs and competition scrimmages have been performed to ensure that these are fully developed and the pilot and co-operator are properly trained.

2.5 Budget

The project budget was projected to be $25,000 based on previous travel and fabrication expenses. Funding for the budget was received through generous sponsorships from the NASA WV Space Grant Consortium, WVU Benjamin M. Statler College of Engineering and Mineral Resources, Lane Department of Computer Science and Electrical Engineering, as well as the stipend received from NASA / NIA. The budget covers all costs associated with the fabrication and travel activities. The approximate overview division of funds is shown in Table 1. All fabrication expenditures were tracked by the faculty advisors and the team's Chief Financial Officer (CFO).

Category	*Estimated Expense ($)*
Mechanical Parts and Drive Train	14000
Computer and Electronics	5000
Travel and Registration	6000
Total Expenditure	**25000**

Table 1 –MRT Budget Overview

3 System Descriptions

3.1 Drive System

3.1.1 Chassis

The MMR employs a split chassis system with four independently driven tracks as the foundation of its drive system. This system does not use springs or pressurized elements, such as hydraulics or pneumatics, making the chassis more viable in most environments encountered during space exploration [4]. Rather, it employs kinematics to maximize traction. The front and rear of the rover are independent, connected via a joint in the center of the chassis. This allows the rover to maintain stability on uneven terrain. An example of this rotation can be seen in Figure 3. The construction technique employed this year allows for a reduction of mass when compared to the prior design based upon rapid prototyping. The design also ensures a stronger and more nimble base with fewer components and points of failure by using a welded aluminum chassis with additional carbon fiber supports. Stringers were also added to decrease the bending moments seen between the attachment points of the motor brackets. Added material at the welded joints was also employed to eliminate unwanted torque in the frame and increase the strength.


Figure 3 – Rendered Side View with Rotation

3.1.2 Propulsion and Steering

Propulsion is provided by four brushless right angle DC gear-motors with built-in electronic speed control. This selection minimized components and is an increase in power providing 1/8 HP each. These motors have an added gearhead 20:1 reduction ratio to provide adequate torque of 35 lb-in while still allowing the rover to move at a brisk pace. The rover is powered by two lightweight, powerful 24V Lithium-ion (Li-ion) drill batteries. The tracks are 325mm in length, 85mm in width, and 160mm high providing ample ground clearance and reliable traction. This ground clearance allows the rover to negotiate 10 centimeter tall obstacles per system requirements. The MMR also meets system size requirements measuring in at 78cm x 72cm x 44cm. To allow for a more versatile system, the tracks can also be quickly changed out with tires.

3.2 Sample Acquisition System

The robotic arm is a 5-joint system. The first joint provides a side-to-side sweeping motion, and the second joint, mounted directly above and perpendicular to the first joint, provides the arm with an up-down lifting motion, while the fifth joint holds the claw. Robotics Dynamixel MX series servos [5] were used to provide more power to help the arm reach a wider range. The servo motors provide an RS485 interface allowing up to a 300 degree range of motion, with a resolution of 0.29 degrees and a repeatability of 2.5mm. This allows for precise position of the gripper which facilitates the acquisition of samples as seen in Figure 4.

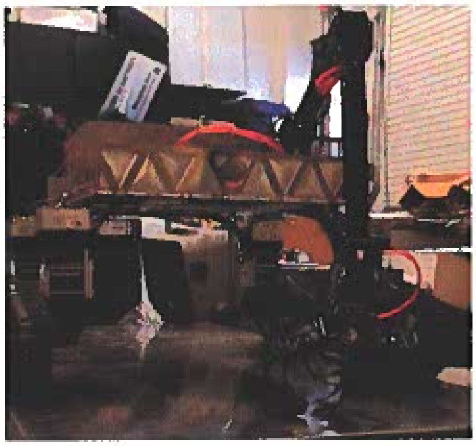


Figure 4 – Robotic Arm Testing Platform

It has been discovered through testing that lining up a sample capture can be particularly difficult when video quality is suboptimal. In order to combat this issue from previous years, each finger will be colored to allow for easier visualization. Stronger servo motors have also been deployed to aid in the lifting of heavier samples. The claw itself will also be smaller in size than previous years in order to allow for more precise movements and ease the collection of smaller samples.

3.3 Control and Communications Software

3.3.1 Control

MMR is controlled by three main pieces of software: the Operator Control Unit (OCU) / Mission Planner, Robot Control Unit (RCU), and Camera Control Unit (CCU). The OCU is executed on a server housed on campus in the mission control room. This software is responsible for displaying telemetry from the rover and serializing operator input to be transmitted to the rotate as seen in Figure 5. The server is also responsible for broadcasting and recording live USTREAM video streams. The OCU is designed to be a TCP/IP Server and was written in C# .NET 4.5 and developed as a WPF application. The OCU software listens for connections from the rover, accepts connections, and transmits commands from the Xbox controllers used by the operators.

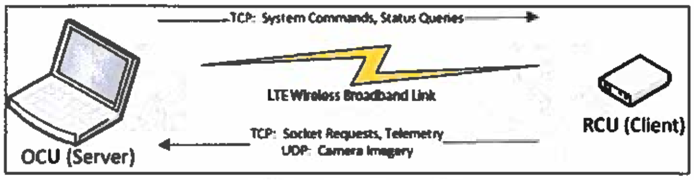


Figure 5 - Communications Diagram for OCU/RCU

The OCU software also has several UDP sockets that are responsible for receiving rover imagery to minimize the bandwidth used.

The RCU application resides on the Microsoft Surface 2, the main On-Board Computer (OBC), and provides robust control interfaces for the servo and motor controllers, camera selection, monitors the state-of-health, adjusts robot performance relative to environmental conditions, and implements autonomous self-sustainment protocols during loss of communication. The connection between the RCU and the arm is established through Robotics USB2Dynamixel controller. Using the provided Dynamixel SDK, commands can be sent directly from the .NET application to the servos. The initial approach using a Robotics CM-700 controller proved to be too much given the time frame and unforeseen issues. The RCU has predefined sequences or macros that the arm control specialist can utilize.

3.3.2 Mission Planner

The mission planner software, developed at WVU, is integrated into the OCU. By integrating these systems, the number of windows required for ideal operation has dropped allowing for a more streamlined software package and mission. This software will allow for the tracking of targets, path planning, and for the time remaining to be known by the operators. The current GUI can be seen in Figure 6. Discovered rocks can also be added by assistants watching prior runs. This system can be tested locally as well by simply changing the map selection from a dropdown box.

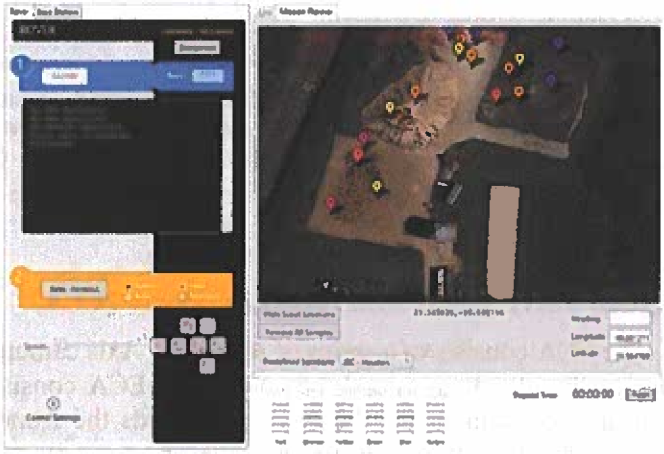


Figure 6 – OCU / Mission Planner

3.3.3 Wireless Communications

MMR employs two CradlePoint IBR-600 modems [6] as the backbone of the communications system. Research and experience has indicated that AT&T maintains a robust network in the Houston area. Due to this, both models utilize AT&T's 4G-LTE Network to maximize transmission speeds. One modem is mobile placed on MMR while the other remains stationary on the base station. The on-board modem also serves DHCP to the MMR network as a precaution

– although all local equipment has a static IP address. The stationary modem employs Wi-Fi to load-balance the MMR internet connection and provide failover in the event of signal loss. The basic diagram of the network is shown in Figure 7 below.

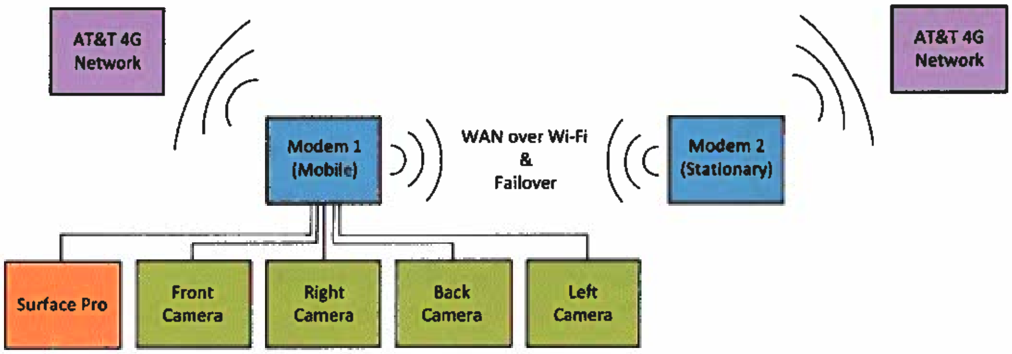


Figure 7 – MMR Network Diagram

Directly affected by our network capacity is the Environmental Camera Array (ECA). According to the camera manufacturer our network needs can vary greatly depending on frame rate and compression. The following table was utilized to analyze network rates required for streaming the ECA.

Compression Rate	10 FPS Mbit/s Requirement	30 FPS Mbit/s Requirement
10%	2.488	5.8
30%	1.48	3.508
50%	0.888	2.164
70%	0.672	1.692
90%	.544	1.388

Table 2 – Bandwidth Comparison

Through analysis, it was apparent given that the bandwidth is available as it was during testing, it would be ideal to operate at the higher 30 FPS with a 10% compression rate. However, in the event that the network characteristics change, this can be changed via the CCU software.

3.3.4 Optic Systems

3.3.4.1 Environmental Camera Array (ECA)

The ECA consists of a series of solid PTZ Axis cameras used to visualize the area around the robot. The ECA consists of 4 cameras, one camera will be directed towards the front of the robot, a camera will look off to each side, and one will be a view out the rear. The capability to switch between multiple cameras on the MMR allows the user to be fully aware of the surrounding environment. Figure 8 shows the ECA layout. The cameras will be assigned static IPs to easily identify them on the network. The camera feed is connected directly to the CradlePoint routers, bypassing the Surface Tablet running the RCU and therefore reducing the processing stress.

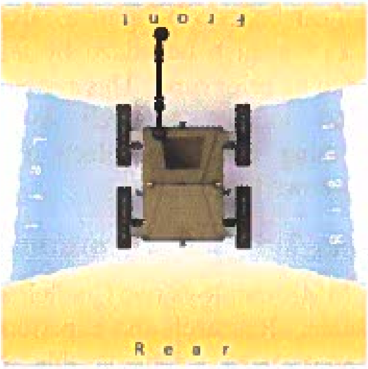


Figure 8 – ECA

3.3.4.2 Camera Control Unit (CCU)

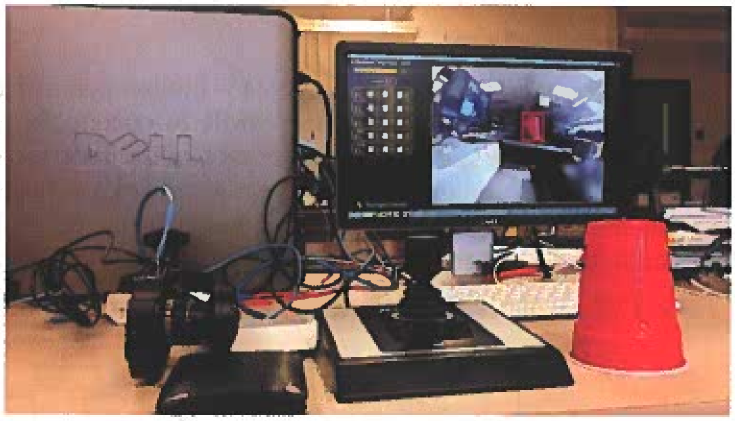


Figure 9 – CCU Example

The CCU is an interface that allows the control of the solid state Axis IP PTZ (Pan, Tilt, Zoom) cameras. Since multiple cameras of the same type are used, each camera previously required a separate instance of the CCU to be viewed. In order to combat this, the Axis Camera Station Client will be used to monitor the incoming video and audio feed. An Axis Joystick Controller provides additional functionalities such as zoom control, pan control, camera selection, and toggling single/split view as seen in Figure 9. Additionally, there also exists two different editions of the CCU due to the use of two different types of cameras (Axis and Panasonic). A panel will control the rock detection algorithm thus enhancing the ability for a user to identify rocks. The algorithm functions by converting the RGB image to its HSV representation. Thresholding is then performed for each color using a defined range. The range for each color can by dynamically changed in real time from the CCU Color panel. Dilation and erosion is applied to each thresholded image. A box is placed around each detected region and then the image is displayed to the user. This functionality can be toggled per driver preference or current mission stage.

3.4 Base Station

Figure 10 – Base Station

The rover will deploy a stationary base station, to assist with communications and sample recognition throughout the entirety of the competition. The rover will bring the base station to a desirable location if the starting point of the competition is not optimal for its purpose. Structurally, the base station will be composed of a lightweight aluminum boom deployment system supported by a composite base. The boom will be deployed from the system once the rover has left the platform and it is allowed to rise. The mast will extend as the boom rises.

Held within an enclosure, not included in Figure 10, on the base station will be a CradlePoint IBR600 AT&T 4G integrated router and a power supply. A Panasonic 72x PTZ IP camera will be mounted to the end of the mast, which will allow an extra camera angle from two meters higher than the highest point of the competition field, to be sent back to the control center in Morgantown and broadcast.

4 Technical Specifications

4.1 Power System

The power system begins with two 24V lithium polymer drill batteries. These two batteries provide 88 W/Hrs each allowing the MMR to operate for the full hour of competition. The schematic shown in Figure 11 allows for each of the batteries to share the load of the system. The power system was designed with multiple redundancies included to allow for possible failure of components. The implementation of an emergency stop in addition to the main switch is due to the need to be able to disable the motors, but not the communications or computer systems.

The 12V regulator is solely for powering the servo's of the arm while the ATX regulator power's the ECA, CradlePoint, fans, Microsoft Surface 2 docking station, and the switch allowing the ECA to connect with the CradlePoint. This can be seen in Figure 12.

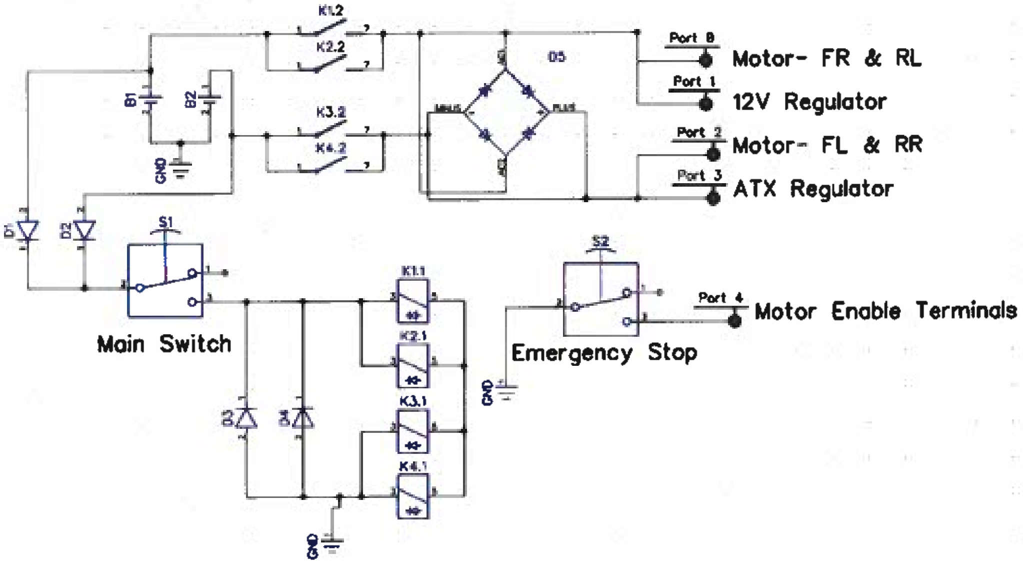


Figure 11 – Redundant Power Balancing Circuit Schematic

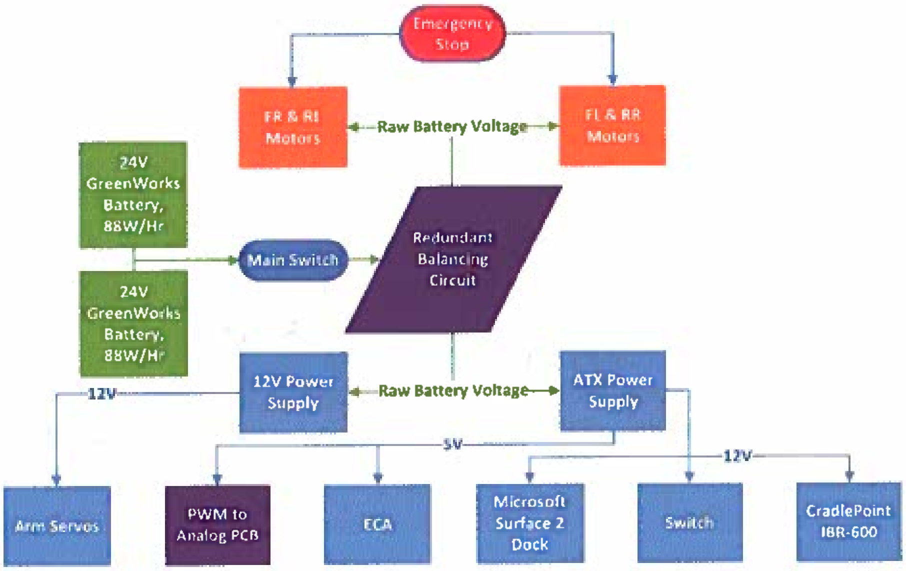


Figure 12 – Wiring Diagram

4.2 Control and Communications Hardware

Communication between the RCU and the motors begins at the Microsoft Surface 2 tablet. The USB port on the docking station then allows connection to a Polulu USB-to-PWM converter. This converter then is used as an input to a Polulu Multiplexer (MUX). A second input coming from an RC-controller is the master of the MUX, or rather the default output until a special selector bit is received from the RCU. The output of the MUX is a PCB that converts the PWM signal into and analog speed and direction for each motor. The PCB schematic can be seen in Figure 13.

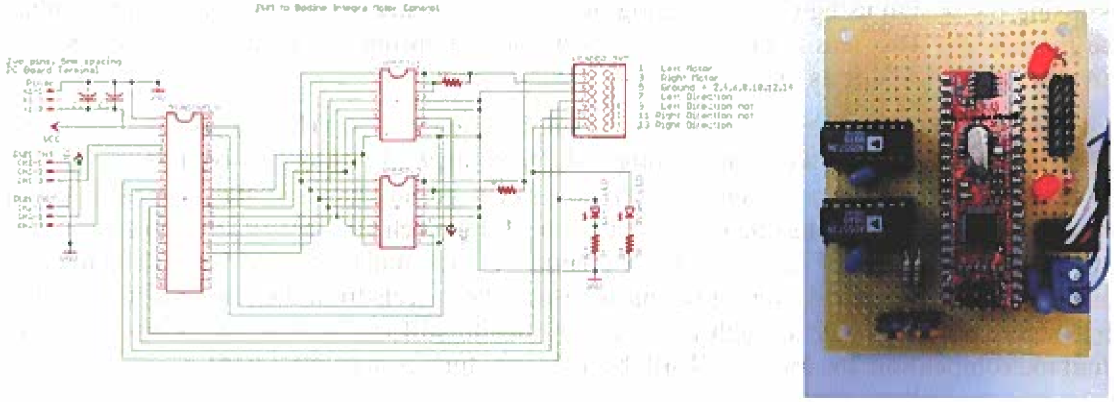


Figure 13 – PWM to Analog PCB

The reasoning for maintaining the PWM conversion is due to the fact that multiple drive types are preferred. A local operator may drive the MMR from an RC-controller until a remote one takes control via the onboard computer. Control is returned to the local operator upon disconnection from the OCU.

4.3 Specifications Table

Technical Specification	Value
Weight – MMR	~ 32kg
Weight – Base Station	~ 8kg
Speed – Tracks	3 ft/sec
Speed - Wheels	9 ft/sec
Power - Batteries	166 Watt/Hr
Operating Time	~ 90 minutes
Drive Motors	1/8HP, 32ft-lb. Torque, 20:1 Right Angle Bodine Gear motors (X4)
Communications	CradlePoint IBR-600
On-Board Computer (OBC)	Microsoft Surface Pro 2

5 Verification and Validation

In order to ensure that the MMR would be competitive, all requirements defined in the definition needed to be met. Verification, the process of ensuring that "selected work products meet their specific requirements" [7] and validation, the process of "demonstrating that a product component fulfills its intended use when placed in its intended environment" [7] were planned and implemented throughout the system development.

5.1 Testing and Modifications

Different test plans were constructed for each subsystem of the MMR. Initially, the MRT began assessing the design using CAD modeling of key components and subsequently an assembly of the full MMR. This was used to verify placement and ensure that loads would be distributed throughout the structure as intended in the original design.

Chassis testing began by performing roll over or tipping tests. The results lead to adding an adjustable roll limiter on the rotating joint. The next stage of testing involved the tracks across various terrains. Across pavement and grass the tracks performed adequately, but upon entering the lunar sand pit used for testing the Mountaineer Mining Vehicles (MMV) the tracks would bind up. This can be seen in Figure 14. Track guards were the initial solution but proved to add too much weight and friction lowering the usefulness. The wheels from the previous rover were the final solution and provide a much lower friction while still maintaining the necessary traction. Until the competition, the tracks will still be tested for further improvements.

The MRR, with full payload, was tested in environments listed in the project requirements: rocks, sand, and a 33% grade. The rover was able to make multiple consecutive traversals across the lunar sandpit, overcome a 6 inch rock, and ascent or descend a rocky 30% grade in addition to a 54% obstacle strewn grade with current modifications.

Considering the MMR has passed the same tests that the previous MRT rover had successfully performed, a comparison has been performed. This has shown that the overall vision and awareness of surrounding has improved while improving the manipulator arm. The weight has also decreased potentially allowing for a better selection of run time at the competition. The MMR is also very modular by comparison and provides multiple redundancies for components and far more torque to the motors.

Figure 14 – MMR Sandpit Testing

5.2 Risk Assessment Matrix

Risk	Category	Effect	Mitigation
Battery discharged below a safe voltage	High	Power system must rely on spare battery	Utilize control hardware and redundant power system
Control or communications power failure	High	Control of the rover will be lost, rendering it useless and unsafe if motors are in on state	Utilize redundant power system and ensure motors stop if control is dropped using a watchdog timer
Arm servo failure	High	The arm may be rendered inoperable	Thoroughly test servos and ensure they met and exceed requirements
Wheel drive motor failure	Moderate	Can reduce lifetime of remaining motors and gearboxes	Utilize independent drive for each wheel and ensure three are strong enough to operate
Main camera failure	Low	Main sample collection view is lost	Ensure collection from side camera is possible

6 Education and Public Outreach

Educational outreach, an important component of the competition and to our sponsors, has been a key goal in the 2015 MRT strategy. Outreach allows us to not only interact with the community, but further teach new members as to the past trials and experiences of the returning members. This year the MRT supported many university activities, local school visitations, and collaborated with various organizations to achieve the outreach goal. The largest of these activities include assisting with 8th grade career day, outside of class activities for current freshman, along with tours and presentations to potential students and field trips. Multiple forms of social media were also implemented including Facebook and Twitter and a website created to further spark interest and engage the community and university.

7 Summary

The MRT is confident with the ability and strength of the new design. These all function above the desired requirements, but testing will continue until the day of the competition to ensure the MMR is ready. Scrimmages will continue to be key in training the operators and the assistants while continuing to verify and validate all systems.

8 References

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9 Appendix:

9.1 System Requirements

ID	Category	Requirement	Required/ Objective
1	Physical	Robot shall fit within a 1m x 1m x 0.5m footprint in a stowed configuration	R
2	Physical	Rover should take less than 15 minutes to deploy	O
3	Physical	Mass shall be less than or equal to 45 kilograms	R
4	Physical	Rover shall be weatherized to withstand light rain	R
5	Operational	Rover should be able to traverse over obstacles up to 10cm in height	R
6	Operational	Rover should be able to negotiate up-slopes and down-slopes of 33% grades	R
7	Operational	Rover should be capable of selectively picking up irregularly shaped rocks with diameters ranging from 2-8cm and masses ranging from 20-150g	R
8	Operational	Rover shall transport at least 10 rocks of 150g mass, 8cm in diameter	O
9	Operational	Rover shall traverse sand for distances exceeding 20 feet	R
10	Operational	Rover shall operate for 1 hour on battery power	R
11	Operational	Rover should be able to navigate the Rock Field, Lunar Craters, Sand Dunes, and the Mars Hill	R
12	C^2	Rover shall have one or more on-board cameras capable of transmitting visual data back to mission control	R
13	C^2	Rover shall have an on-board microphone capable of transmitting audio data back to mission control	R
14	C^2	Rover shall be controlled remotely based solely on data, including video, gathered from the rover itself	R
15	C^2	Rover shall incorporate a robust communications architecture through use of a wireless broadband card, mobile hotspots, or USB broadband devices	R
16	C^2	Rover should be able to operate for an entire hour in the JSC Rock Yard without the loss of communications	O