

# 2016 RASC-AL Exploration Robo-Ops Student Challenge

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## Final Report

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

**Student Team:** David-Michael Buckman, David Cutright, Devyn Gentzyel, Matthew Grubb, Steven Hard, Maneesh Chandu Jasti, Brittany Johnstone, Ajay Krishna Teja Kavuri, Eric Loy (Team Lead), John Lucas, Matthew Lundquist, Nicholas Mireles, Priyashraba Misra, Nathan Owen, Rohit, and Bertrand Wieliczko

**Faculty Advisor:** Dr. Powsiri Klinkhachorn

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## 1 Introduction

The 2016 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 May at the 2016 Exploration Robo-Ops competition. The team is currently in the verification and validation stage.

WVU’s new competition rover, the 2016 Mountaineer Mars Rover (MMR-16), had an initial requirement set by the team and advisor to improve certain aspects from the previous rover. This involved a lightweight aluminum chassis design with increased mobility and construction from a proven system. Goals included optimization of the chassis, modular design, assembly and disassembly, communications, and traction. This was achieved by using a split-chassis design, interchangeable drive system, improved wireless modem, and a variety of other modifications.

The MMR-16 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 three major subsystems: drive, sample acquisition, and control and communications (C<sup>2</sup>). 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 2015 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 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 is 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 from majors including 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 of 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 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).

## 2.3 Concept of Operations

The concept of operations describes the operators’ and rover’s progression during the mission to accomplish objectives. The mission objective of the rover is to traverse the simulated planetary surfaces at the JSC Rock Yard, find and 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. Figure 2 illustrates this algorithmic approach. As long as time remains, the rover will explore the site until a sample is found. Once a sample is discovered, the rover will traverse to

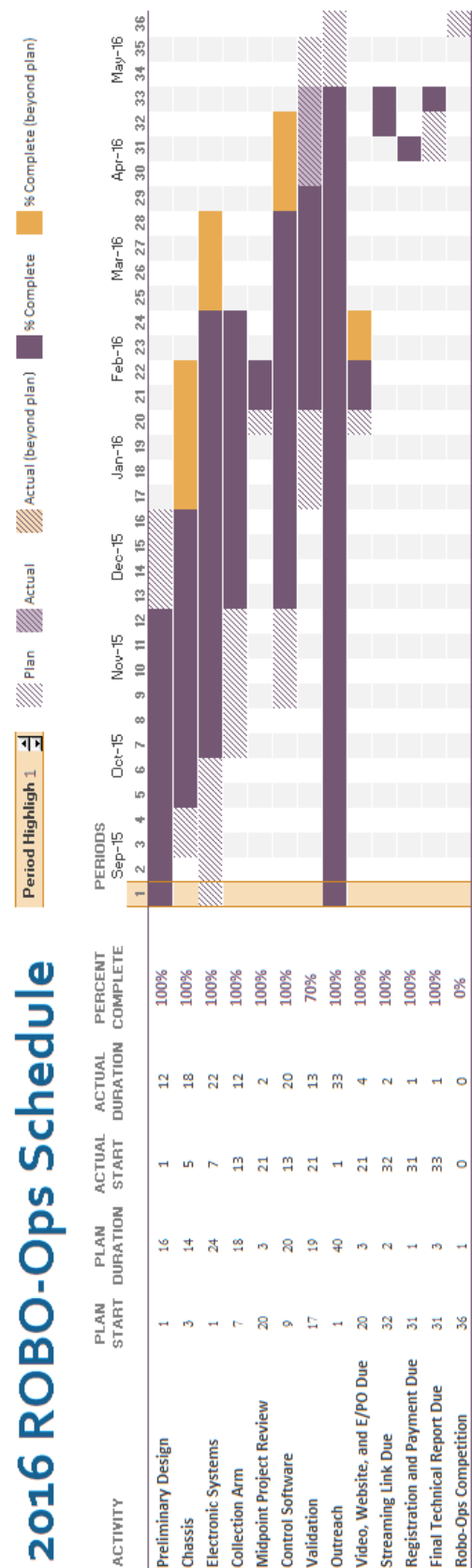


Figure 1: Project Schedule Overview

its location and attempt to acquire it. If the orientation of the rover is optimal then the manipulator system will seize the target. If the orientation is suboptimal then adjustments will be made if it is worth the time for that particular sample. If not, the rover will abort and continue searching for other samples. When time is running low and the run is drawing to a close, the rover will return to the starting area and finish the run.

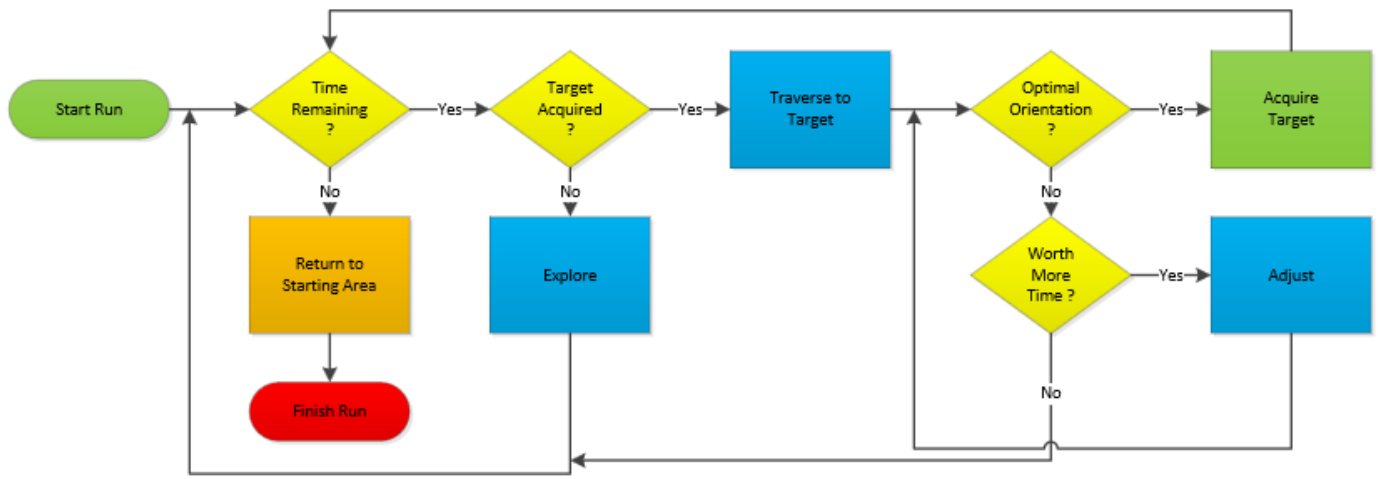


Figure 2: Concept of Operations Flow Chart

## 2.4 Mission Control Operational Plan

Mission control will be staffed, at minimum, by a team of two operators. The first will be the main operator or driver whose primary goal is to maintain a known orientation and position 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. These two operators will control the rover from the computer in the corner of the room shown in Figure 3. Any additional members will assume the role of assisting the operators with their duties and providing moral support. Additional members will utilize the large display on the wall, also shown in Figure 3, to carry out these tasks and aid the operators. 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 shall have the final call in any decision making that needs to occur. Should a contingency to the plan occur, the assistants and co-operator will be solicited for any alternate ideas before the decision is finalized. 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.



Figure 3: Mission Control



## 2.5 Budget

The 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 division of funds is shown in Table 1. All fabrication expenditures were tracked by the faculty advisor and the team's Chief Financial Officer (CFO).

**Table 1: MRT Budget Overview**

| Category                       | Estimated Expense (\$) |
|--------------------------------|------------------------|
| <b>Equipment and Supplies</b>  | 17,500                 |
| <b>Travel and Registration</b> | 5,500                  |
| <b>In-Kind Support</b>         | 2,000                  |
| <b>Total Expenditure</b>       | <b>25,000</b>          |

## 3 System Descriptions

### 3.1 Drive System

The MMR-16 employs a split chassis system with four independently driven wheels and four powerful steering servos 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 smooth kinematics coupled with aggressive tires and steering mechanisms to maximize traction and maneuverability. The entire rover, weighing in around 29.7 kg, is powered by two lightweight 48V Lithium-ion (Li-ion) batteries. The outside diameters of our tires are 246 mm and the way the drivetrain is attached to the chassis provides one foot of ground clearance. This ground clearance allows the rover to negotiate 10 centimeter tall obstacles per system requirements. MMR-16 also meets system size requirements measuring in at 98 cm x 82 cm x 49.5 cm.

#### 3.1.1 Chassis

The front and rear sections of the rover are independent, connected via a slewing ring bearing in the center of the chassis. This allows the rover to maintain stability on uneven terrain. An example of this articulation can be seen in Figure 4. The construction this year allows for a reduction of mass when compared to the prior design. The design also ensures a stronger and nimbler base with fewer components and points of failure. Two tubular aluminum frames make up the structure of the MMR-16. Two carbon fiber plates are attached to the ends of the frame and are connected to each other via the slewing ring. The design also ensures a very strong base



**Figure 4: Side View with Rotation**

by mounting a custom bent 1.5 mm aluminum sheet to the bottom of the tube chassis with additional aircraft grade plywood supports laminated with both carbon fiber and Kevlar materials. This reduced mass considerably compared to the solid aluminum used for the body of last year's rover.

### 3.1.2 Propulsion and Steering

Propulsion is provided by four brushless Maxon DC motors with planetary gearheads and separate, but highly effective, speed controllers with an electronic brake [5]. They provide a torque of 46 kg-cm while still allowing the rover to move at a brisk pace at a maximum speed of 1.4 meters per second. The gearheads have a 111:1 reduction ratio, which cause the motor shafts to spin at approximately 100 RPMs. The new motors are a fifth of the mass of last year's motors and provide more torque.

Steering is provided by four rugged Torxis i00600 servos [6]. These additions caused an increase in mass to MMR-16's overall design, but it was decided that steering mechanisms were necessary to rectify the violent skid-steer turning and decreased maneuverability seen in last year's rover. These powerful devices are able to output a real continuous torque of 115 kg-cm and have shown great promise in field tests with various terrains. With up to a 230 kg-cm peak torque, there is not much that will stop our rover from turning.

MMR-16 is also designed to support various driving modes, seen in Figures 5, 6, and 7, which we have dubbed normal, rotate, and translate mode. In all modes the operator can control motor speed, but in normal mode the operator has control over the turning radius of the rover through direct manipulation of the steering servos. In this mode both front wheels turn at a particular angle and both rear wheels turn opposite that angle, which enables the rover to travel on various circular or linear paths. We limit the turn angle to be about 30 degrees in either direction with respect to the anterior direction. In rotate mode the front wheels turn inward towards each other until they are at about 45 degrees with respect to the anterior direction. The rear wheels do the same, but they will turn outward away from each other. This allows the rover to turn in place and can be particularly useful to the operator when the robot is in confined spaces like the Mars Yard. The last mode of operation, which we call translate mode, turns all the wheels 90 degrees from forward to allow the rover to move sideways.

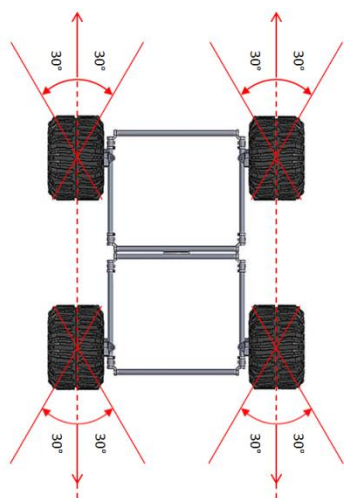


Figure 5: Normal Mode

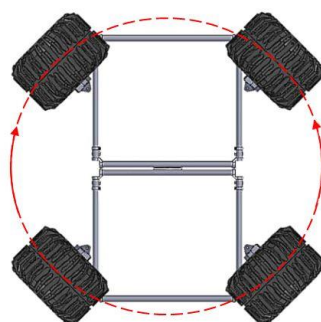


Figure 6: Rotate Mode

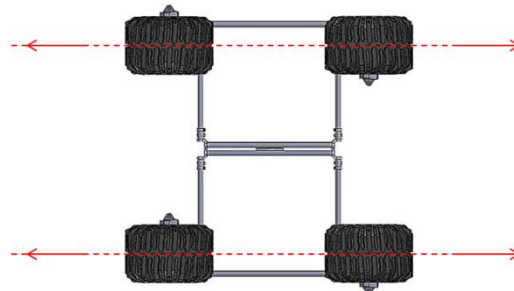


Figure 7: Translate Mode

## 3.2 Manipulator System

The robotic arm is a 5-joint, 5-degrees-of-freedom 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. The third joint behaves like an elbow in the sense that it can bring the end effector closer to or further away from the arm base on the rover. The fourth and fifth joints are essentially part of the end effector. The fourth joint provides up and down motion near the end effector while the fifth joint is responsible for opening and closing the actual gripping mechanism. Robotics Dynamixel MX series servos [7] 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° range of motion, with a resolution of 0.29 degrees and a repeatability of 2.5mm. This allows for precise positioning of the gripper which facilitates the acquisition of samples as seen in Figure 8.



Figure 8: Sample Acquisition

It has been previously discovered through testing that lining up a sample capture can be particularly difficult when video quality is suboptimal. As a continued solution to this issue, each finger will be colored to allow for easier visualization. Control is facilitated through a new OpenCM9.04 board [8], which will allow for computer or Bluetooth control without having to change any major connections. Stronger servo motors have also been deployed to aid in the lifting of heavier samples and a slewing ring base aids with overall stability. The elbow proved weak during last year's competition and over-torquing requiring a reset of the arm. The new servo should alleviate that problem.

## 3.3 Control and Communications

### 3.3.1 Control

The MMR has 3 main pieces of software that have been developed and refined by WVU students over the past couple of years to tele-operate the rover for the RASC-AL competition. The Operator Control Unit (OCU), which incorporates the Mission Planner, the Robot Control Unit (RCU) and the Camera Control Unit (CCU).

The OCU is run on a desktop computer that has been hosted on the WVU campus in the mission control room. The computer is connected to a large flat screen television to provide the operators with an expansive view of the camera feeds. The OCU is responsible for displaying telemetry from the rover, interpreting user input into commands for the rover, and serializing the commands to be transmitted to the rover via LTE wireless links.

The OCU implements a TCP/IP server, written in C#, using the .NET 4.5 Framework, and is developed as a Windows Presentation Foundation (WPF) application to provide a functional graphical user interface (GUI). The OCU uses the Microsoft XNA Framework to interface with the Xbox 360 controllers [9] that are used to drive the rover and operate the arm. The OCU software listens for connections from the RCU, when a connection is established, the OCU allows the operator to take control of the Rover and send commands to the rover. For the purposes of debugging and redundancy, the OCU uses the keyboard as a secondary method of operator input to control the rover.



The RCU is run on a Microsoft Surface 2 [10] because it is self-contained and easy to swap out. The Surface is the main On-Board Computer (OBC) for the rover. The RCU provides a robust control interface for the rover's subsystems. To communicate with the OCU, the RCU implements a TCP/IP client that establishes a connection to the OCU and deserializes the commands sent from the OCU. The OCU then routes the commands to the appropriate subsystem. In the event of a loss of communication, the RCU implements autonomous self-sustainment protocols to allow the operator to reconnect and take control of the rover.

Communication between the RCU and motors starts with the Microsoft Surface 2 tablet, which can be seen in Figure 9. The tablet is connected via Ethernet to the Peplink MAX HD2 Mini [11] so it is OCU controllable. A USB port on our Surface docking station allows for connection to a USB hub. That hub then connects to a Pololu USB-to-PWM converter called a Maestro [12] to send PWM signals for an input selector, speed, radius, and drive mode. These signals are inputs to a Pololu Multiplexer (MUX) [13] in addition to lines from a radio control (RC) receiver. The reason for this is that multiple drive types are preferred. A local operator can drive MMR-16 using an RC-controller until a remote operator takes control via the onboard computer. The local operator regains control of MMR-16 once the remote operator disconnects from the OCU. The MUX defaults to RC-controller input, but the input selector signal is used to allow the RCU to take control of the rover. The outputs of the MUX are sent to a custom PCB shown in Figure 10 that converts the output signals into an analog speed and direction for each of the motors as well as positional values for each of the steering servos and brake toggling.

The connection between the RCU and the arm, seen in Figure 9, is established through USB to a ROBOTIS OpenCM9.04 board that has been flashed to be compatible with Dynamixel commands. Using the Dynamixel SDK, commands can be sent directly from the RCU to the servos. The RCU has macros that the arm control specialist can utilize to automate certain parts of the collection process. This control board also allows operation with a local Bluetooth controller. This was desirable so the arm could be demonstrated without a remote link, much like the reasoning behind the RC controller.

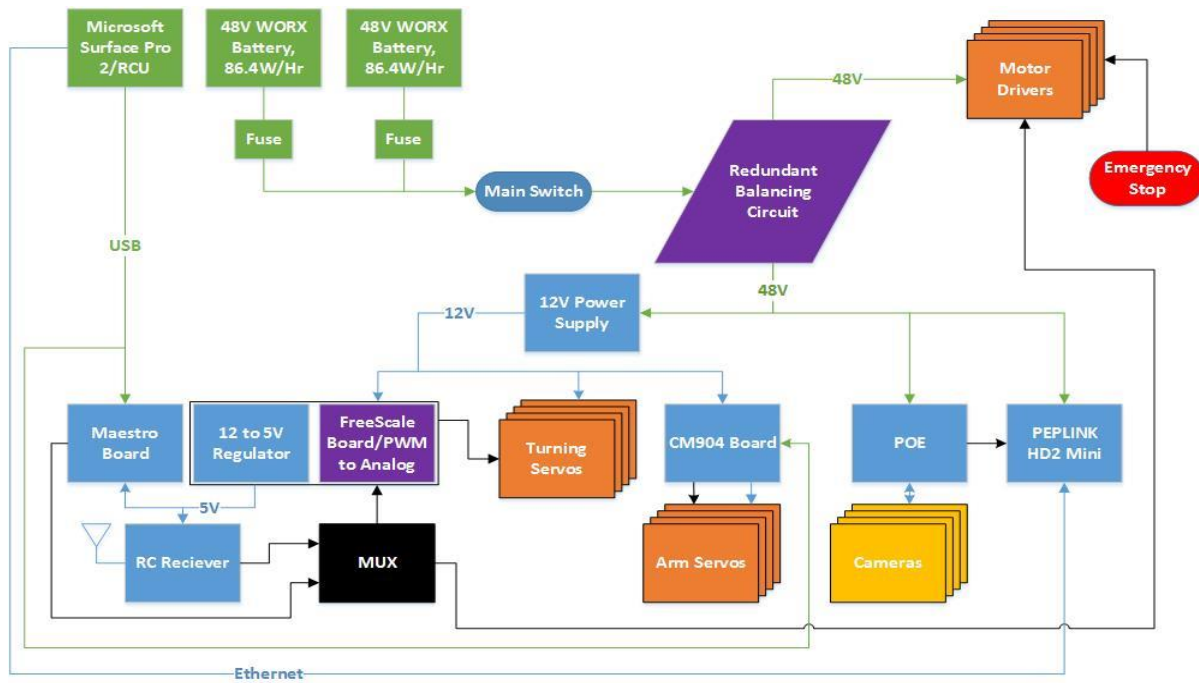


Figure 9: Wiring Diagram

Other connections depicted in Figure 9 are the cameras to the wireless channel, the emergency stop on the motors, and the power system of the rover. The cameras are powered by a power over Ethernet board, and this board sends the feeds to the Peplink, which allows the cameras to be accessed over the wireless channel from mission control. The e-stop connection allows the power for the motors to be disabled without shutting down the entire rover's power system, and the power system itself will be discussed in a later section.

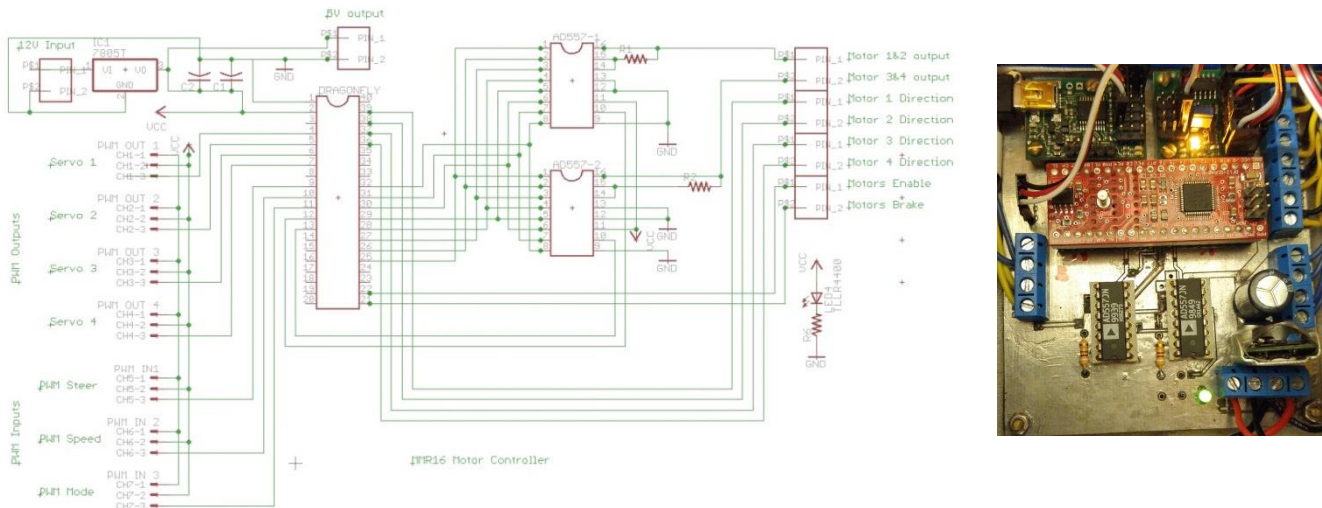


Figure 10: PWM to Analog PCB with Maestro and MUX Mounted

### 3.3.2 Wireless Communications

MMR-16 employs two Peplink products as the backbone of the communications system to create a link shown in Figure 11 from the rover to the operators. Local to the MMR-16 is a Pepwave MAX HD2 Mini dual cellular 4G LTE modem. This modem was selected as previous experience has shown that while AT&T maintains a robust network in the area, throughput is seemingly limited at the competition venue. As a result, the HD2 Mini utilizes one SIM card on AT&T's network and an additional SIM card on Verizon's network. This set-up also protects against any single network failure by a wireless carrier. On the remote end of the connection at WVU is a Peplink Balance 210 router [14], which aggregates multiple WAN connections.

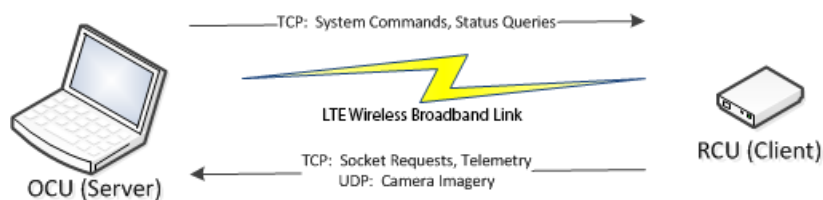
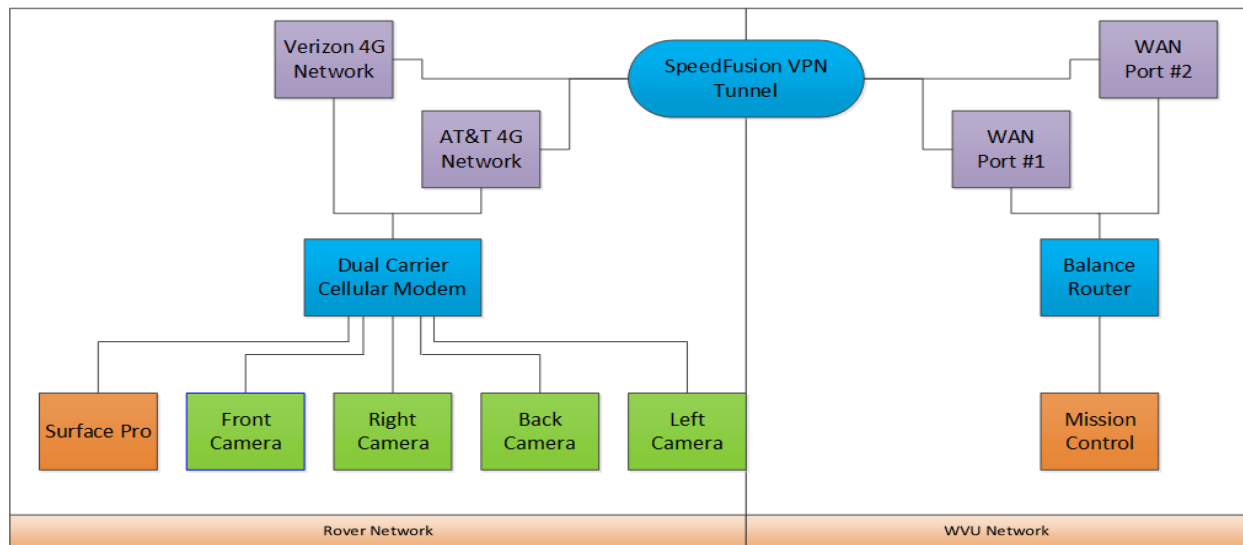


Figure 11: Communications Diagram for OCU/RCU

This entire set-up shown in Figure 12 is significant as the hardware implements Peplink's SpeedFusion technology, which is a proprietary VPN and packet bonding service. SpeedFusion VPNs require Peplink hardware to terminate both ends of the VPN tunnel. The tunnel is transparent to the computing equipment local to the rover and remotely at WVU, which allows

all devices to believe they are on the same local area network. Additionally, traditional load-balancing occurs with each service request by an end-user. Packet bonding allows packets for a single request to be sent over multiple links to make better use of the aggregate available throughput.

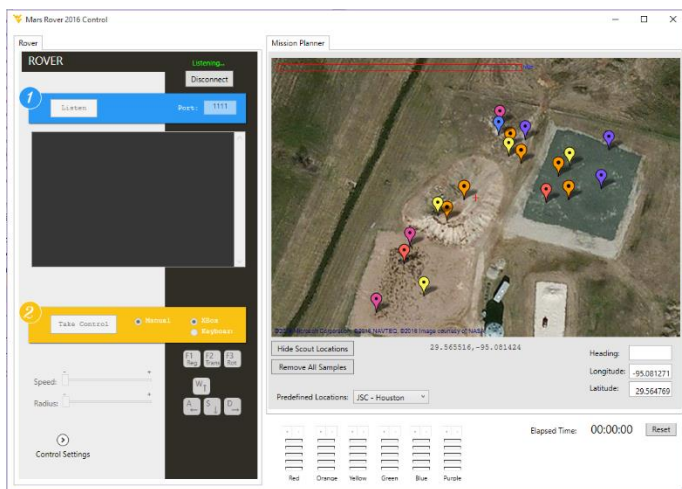


**Figure 12: MMR Network Diagram**

Directly affected by our network bandwidth is the Environmental Camera Array (ECA). According to the camera manufacturer our needs can vary greatly based on frame rate and on-board camera compression. While compression is desirable to save on bandwidth, it also induces a processing latency on the video feed. While we can test the effects at our home campus, the end settings will depend heavily on network conditions in Houston. Our goal is to utilize as much bandwidth as possible without a noticeable deterioration in dropped frame rate at 30 fps. Should bandwidth degrade, less important cameras may have their feeds halted. Testing so far has shown favorable results with moderate signals on both SIM cards. The cellular modem has seen average download speeds of 27.3 Mbps and upload speeds of 11.1 Mbps indoors, which is superior to that of last year’s cellular setup that seldom reached speeds of five Mbps in either direction.

### 3.3.3 Mission Planner

The mission planner software, developed at WVU, is integrated into the OCU. By combining the Mission Planner and the OCU, we have reduced the number of application windows required for ideal operation, which, in turn, allows for a more streamlined software package and easier operation. The software will allow for the tracking of known rock locations and can display the rover’s telemetry, using the GPS built into the Peplink cellular modem. The Current GUI can be seen in the Figure 13. Waypoints to discovered rocks can be



**Figure 13: OCU / Mission Planner**

added by crews watching prior runs. Various locations can be selected simply by changing the map selection from a list of pre-selected locations located in a dropdown box.

The initial plan/tactical strategy for sample collection is to go down Mars Hill and through the Sand Dunes first while searching for samples. After the area is searched for maybe 10 minutes, we will rush to the Mars Yard where we will spend most of our time (approximately 25 minutes). The Lunar Craters will then be searched for 10-15 minutes, and with the time remaining we will get the rover back to the top of Mars Hill. We will acquire any samples we see on the way back to the start position and search the top of Mars Hill in the end before actually stopping. However, an optimal path will be generated based on the known rock locations and will serve as our adaptive plan in case we veer from the original one.

### 3.3.4 Optic Systems

#### 3.3.4.1 Environmental Camera Array (ECA)

The ECA encompasses a series of Axis M3007 electronic PTZ [15] with wide angle 180 degree lenses 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 stationary cameras allows the user to switch viewing sides instantaneously. Figure 14 shows the ECA layout on the robot.

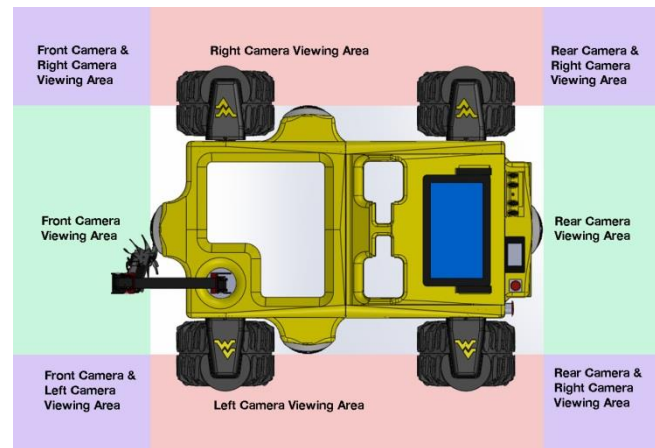


Figure 14: ECA

#### 3.3.4.2 Camera Control Unit (CCU)

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 all the incoming video and audio feed. All cameras feed can be seen at the same time. An Axis Joystick

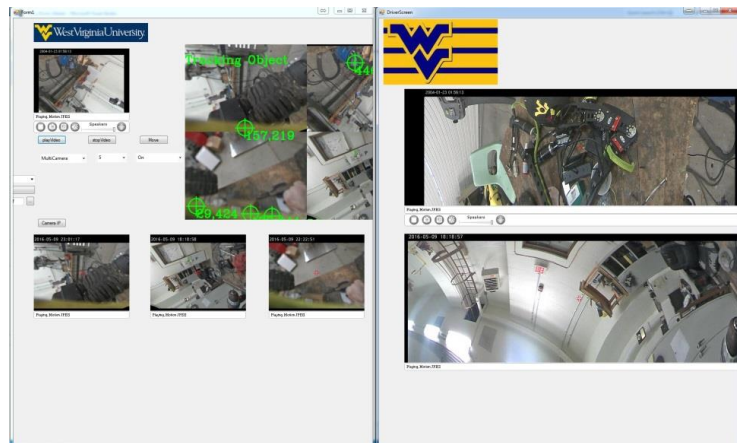


Figure 15: CCU Interface

Controller provides additional functionalities such as zoom control,

pan control, camera selection, and toggling single/split view as seen in Figure 15. A panel will control the rock detection algorithm thus enhancing the ability for a user to identify rocks. The Algorithm uses OpenCV which is one of the vastly used open source computer vision and machine learning software library. The Original RGB image is converted into HSV image for color Detection. Based on the color being detected a threshold image matrix is created for each color separately and the recombined in the end. Dilation and erosion is applied to each threshold



image. A circle 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.

## 4 Technical Specifications

### 4.1 Power System

The power system begins with two 48V Li-Ion weed trimmer batteries [16] that go to two protective fuses. These two batteries provide 86.4 W/Hrs each, allowing MMR-16 to operate for the full hour of the competition. The schematic shown in Figure 16 allows the two batteries to share the load of the system. The diode connected to each battery electrically isolates the batteries from one another so that a battery at a higher energy level cannot charge a weaker battery. The output of the diodes connects to the main power switch, which provides the input to two relay coils. When the switch is on the relays are energized and they close allowing the batteries to power the rover. The battery power goes through a bridge rectifier that we have wired to act as a balancing circuit so that the system can run on one battery or two. The robot uses a power supply that is capable of taking in 48V and converting it to 12V. The 12V sections are used to power the four turning servos attached to the wheels as well as powering the signal board and the board that controls the arm. The other 48 volt peripherals include the motor controllers for the Maxon motors, the POE that powers all four Axis cameras, and the Peplink cellular modem for establishing the network.

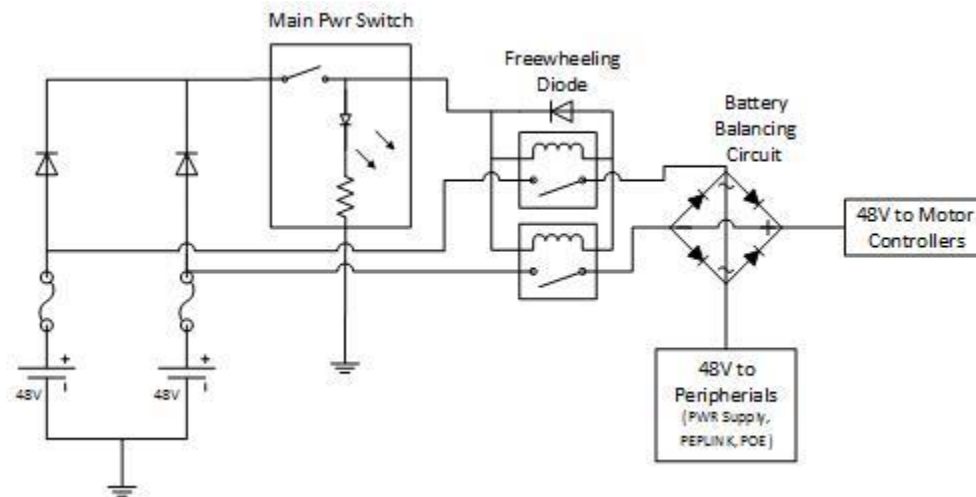


Figure 16: Redundant Power Balancing Circuit Schematic

### 4.2 Specifications Summary

Table 2 outlines all the specifications of MMR-16 and the orthographic view showing dimensions can be seen in Figure 17.

Table 2: Technical Specifications

| Technical Specification | Value                |
|-------------------------|----------------------|
| Weight – MMR-16         | ~ 29.7kg             |
| Speed – Wheels          | 1.4 m/sec            |
| Dimensions              | 82cm x 98cm x 49.5cm |



|  |   |
|--|---|
| <b>Ground Clearance</b>                      | 30.5 cm   |
| <b>Steepest Slope Tested on</b>              | 100 % grade (45 degree incline)   |
| <b>Max Acquisition Range from Rover Body</b> | 45.72 cm  |
| <b>Power – Batteries</b>                     | 170 Watt/Hr   |
| <b>Operating Time</b>                        | ~ 80 minutes  |
| <b>Drive Motors</b>                          | 46 kg-cm torque Maxon DC Brushless Motors with 111: 1 Planetary Gearheads |
| <b>Steering Servos</b>                       | Torxis i00600 Heavy Duty Rotary Servo with 115 kg-cm continuous torque    |
| <b>Communications</b>                        | Peplink MAX HD2 Mini  |
| <b>Average Download Speeds</b>               | 27.3 Mbps   |
| <b>Average Upload Speeds</b>                 | 11.1 Mbps   |
| <b>On-Board Computer (OBC)</b>               | Microsoft Surface Pro 2   |

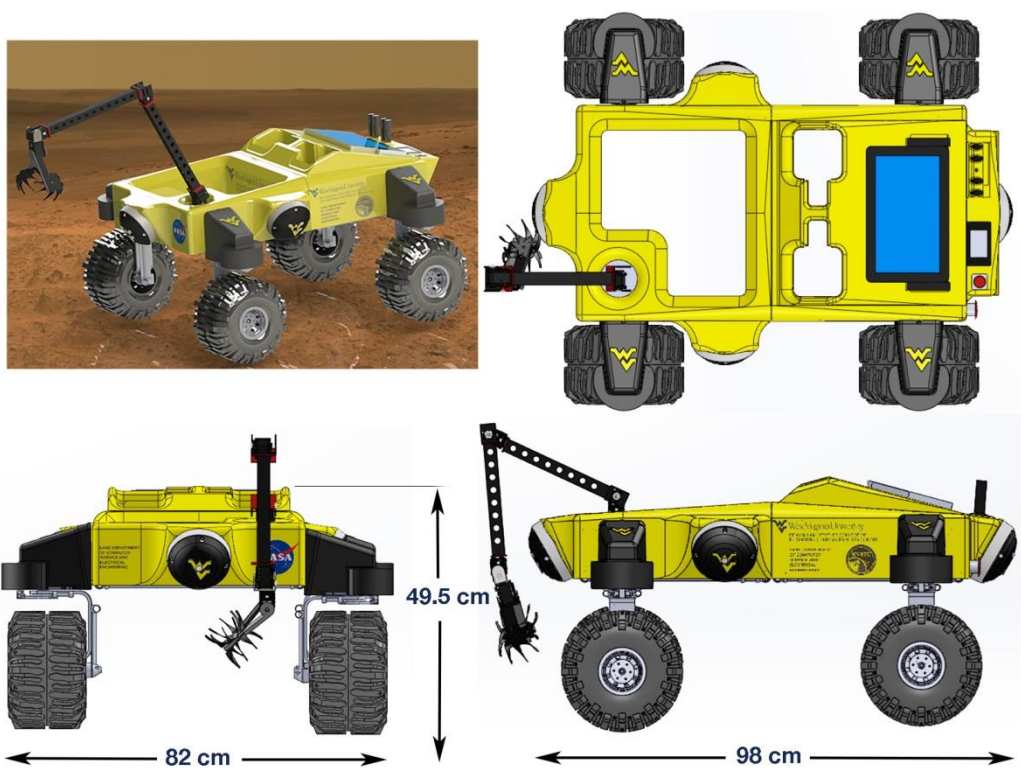


Figure 17: Dimensions

## 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” [2] and validation, the process of “demonstrating that a product

component fulfills its intended use when placed in its intended environment” [2] were planned and implemented throughout the system development.

## 5.1 Testing and Modifications

When designing the MMR, much thought and careful planning was put into place to using the lessons we have learned over the past couple of years of designing and building rovers for this competition. Using the lessons learned, we designed a prototype rover with basic radio control to test the basic design as a proof of concept. This can be seen in Figure 18. Using this crude prototype, we were able to climb & descend a 100% grade, navigate rocky terrain, and, using the split body design, navigate boulders over 10 cm high.



Figure 18: Initial Prototype

With the success of our first prototype, we designed a second prototype to test the new steering mechanism as well as the new power subsystem. At this stage, we also changed the tires to a new, more aggressive grip, which helped the rover navigate over grassy and rocky terrain. This can be seen in Figure 19. Using this new prototype, we confirmed that the rover could operate in the environments listed in the project requirements. At this stage we tested the three modes of operation and fixed any bugs we found in the software.

Spurred on by the success of our second prototype, we modified the aluminum frame of the second prototype to be slimmer and integrated all the power and steering subsystems to make the final rover that has been shown throughout this document.

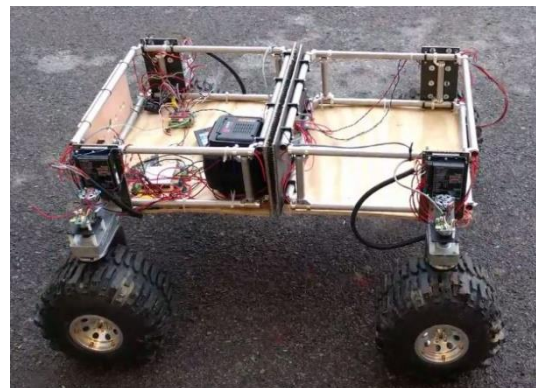


Figure 19: Second Prototype

Throughout the course of testing the rover, the shafts on the motors became bent due high impact forces on the 6mm shaft, forcing us to change our mounting mechanism to add support for the wheel hubs. This reduced the amount of load on the motor shafts and allows for smoother operation. The fix shown in Figure 20 involved mounting a custom machined aluminum tube to the face of the motor. A bearing was used between the tube and the wheel hub to couple the weight onto the face of the motor instead of the shaft itself. Another issue exposed through testing is that the set screws failed to hold the shaft extender to the shaft itself and a wheel fell off. The solution to that has not been implemented as of this moment but will involve inserting a coil pin through the 6mm shaft.

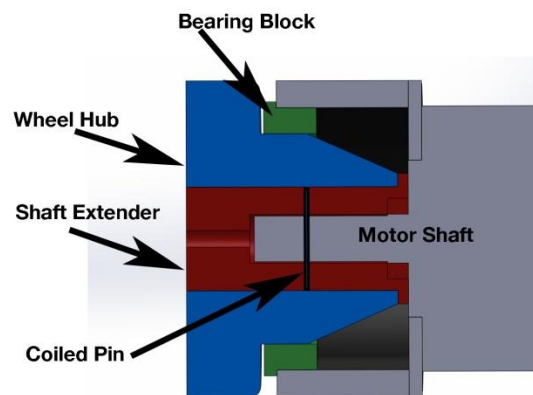


Figure 20: Axial Load Support System

Our initial design called for a carbon fiber base to mount the physical subsystems. We noticed that the power subsystem exhibited a large heat output and required a larger heatsink than what it was provided

with. To rectify the situation, we used a large piece of aluminum and attached the power subsystem directly to the aluminum to provide a larger surface to radiate heat.

Once all these fixes were implemented, we performed endurance tests to verify the duration of operation of the rover. This test verified that the rover could operate the length of the competition.

Using the results from last year as a benchmark, this year’s rover has achieved similar or better results in all aspects of design and operation. This year’s rover is lighter by almost 5 kg, has 3 modes of operation (normal, rotate, and translate), and stronger servos in the arm to facilitate sample collection. These improvements may allow for a better run time and more samples to be collected. MMR-16 is designed to be modular, allowing for easy replacement of mission critical components. MMR-16 also has redundancies for mission critical components that are unable to be easily replaced.

## 5.2 Risk Assessment Matrix

Table 2: Risk Assessment Matrix

| Risk   | Category | Effect   | Mitigation   |
|--|----------|--|--|
| <b>Battery discharged below a safe voltage</b> | High     | Power system must rely on spare battery  | Utilize control hardware and redundant power system  |
| <b>Control or communications power failure</b> | 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 |
| <b>Arm servo failure</b>                       | High     | The arm may be rendered inoperable   | Thoroughly test servos and ensure they met and exceed requirements                                 |
| <b>Wheel drive motor failure</b>               | Moderate | Can reduce lifetime of remaining motors and gearboxes  | Utilize independent drive for each wheel and ensure three are strong enough to operate             |
| <b>Main camera failure</b>                     | 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 2016 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 WVU EngineerFEST, Tekkids, many high school visitation days, outside of class activities for current freshman, tours/presentations to potential students and field trips as well as showing the robots at local events such as NASA S.P.A.C.E. Day, the NRCCE energy conference, Women of WVU event, and NASA day at the new baseball stadium. 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 testing has provided valuable insight into the ability of the motors, battery, and chassis system. For example, the original motor controllers were not good enough to hold our rover in place on a hill, so we had to upgrade to a controller with an electronic brake to keep from rolling down steep grades. 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-16 is ready. Scrimmages will continue to be key in training the operators and the assistants while continuing to verify and validate all systems.

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## 9 Appendix:

### 9.1 System Requirements

| ID | Category       | Requirement  | Required/<br>Objective |
|----|----------------|--|------------------------|
| 1  | Physical       | Rover must fit within a 1m x 1m x 0m5m footprint in a stowed configuration   | Required               |
| 2  | Physical       | Rover must have a mass less than or equal to 45 kilograms  | Required               |
| 3  | Physical       | Rover should be able to operate in light rain  | Required               |
| 4  | Operational    | Rover should be able to traverse over obstacles up to 10cm in height   | Objective              |
| 5  | Operational    | Rover should be able to negotiate up and down slopes having 33% grade  | Objective              |
| 6  | Operational    | Rover should be capable of selectively picking up irregularly shaped rocks with diameters ranging from 2-8cm and masses ranging from 20 to 150gm.    | Objective              |
| 7  | Operational    | Rover should be capable of traversing sand for a distance of at least 20 feet on slopes between 5 and 15 degrees.                                    | Objective              |
| 8  | Operational    | Rover shall operate for one hour on battery power  |                        |
| 9  | Operational    | Rover cannot be powered by an internal combustion engine   | Required               |
| 10 | Operational    | Rover should be able to navigate the Rock Field, Lunar Craters, Sand Dunes, and the Mars Hill  | Objective              |
| 11 | C <sup>2</sup> | Rover must have one or more on-board cameras capable of transmitting visual data back to mission control   | Required               |
| 12 | C <sup>2</sup> | Rover must have an on-board microphone capable of transmitting audio data back to mission control  | Required               |
| 13 | C <sup>2</sup> | Rover will be control remotely based solely on data, including video, gathered from the rover itself   | Required               |
| 14 | C <sup>2</sup> | Rover shall incorporate a robust communications architecture through the use of a wireless broadband card, mobile hotspots, or USB broadband devices | Objective              |