BENJAMIN M. STATLER COLLEGE OF
ENGINEERING AND MINERAL RESOURCES

BLUEFIELD STATE
COLLEGE

2013 NASA/NIA RASC-AL Exploration Robo-Ops Student Challenge Final Report

West Virginia University
Statler College of Engineering and Mineral Resources
in collaboration with Bluefield State College

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1 Introduction

The 2013 Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) Exploration Robo-ops Competition purpose is to challenge university teams to build and demonstrate a planetary rover at the Johnson Space Center (JSC) Rock Yard. The competition supports the NASA mission "to engage the public in its missions and research" by requiring teams to engage the public through use of social media, an informative project website, streaming video from the competition, and performing outreach activities [1].

The rover project was chosen as the focus of two courses offered at West Virginia University (WVU): a special topics course offered to undergraduate students and an advanced topics course offered to graduate students, both titled *Experimental Robot Design*. The team included students from these courses, cadets from Air Force ROTC Detachment 915 and 2 students from our partner institution, Bluefield State College. The team consists of students from varying disciplines including: aerospace, civil, computer, electrical, mechanical, and systems engineering as well as computer science.

The rover features carbon-fiber composite and aluminum construction, six-wheel independent drive, four-wheel steering, and rocker-bogie suspension; shown in Figure 1. It incorporates a Navigation Assistance System (NAS) and Object Identification Software (OIS) that increases navigation precision and provides useful feedback about the mission environment to the operator. The rover houses a sample-acquisition system comprising a 3 degree-of-freedom arm with fisheye camera installed to better assist the operator in sample acquisition. The communications framework employs a wireless CDMA modem to allow operators to control the rover from WVU while it is in the JSC Rock Yard and simulate the data lag present in interplanetary communications.

Figure 1: WVU Mars Rover

This Technical Report defines the systems engineering process followed by the team, the development of the rover from requirements development to fabrication, and the overall system design broken down into three major subsystems: Drive, Communications, and Sample Acquisition. It also details the team's Education and Public Outreach activities.

2 Systems Engineering

The Mountaineers Rover Team began the systems engineering process upon initiation of the project proposal effort late in the Fall 2012 semester. Initial requirements analysis lead to a preliminary design presented in our project proposal. The project kicked off upon reward of a competition spot in December and the development of the proposed design commenced in January 2013. This necessitated implementation of an aggressive nineteen week schedule and a solid systems engineering process. 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 project 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.

The project required the contributions of students spread across different engineering departments, and with different academic concentrations. 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]. The team's project plan details the project goal, 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. Components of the plan are included in this paper: Budget in Section 2.2, Schedule in Section 2.3, Requirements Definition in Section 2.6, and Risk Assessment in Section 2.7.

2.1 Project Scope

In order to establish estimates of the project planning parameters, the project management team first estimated the scope of the project by developing a work breakdown structure (WBS). The WBS is a product-oriented structure which divides the project into more manageable components [2]. The skill set of each team member was assessed and tracked in our team roster so that tasking could be assigned to qualified candidates. The WBS was used to develop the project schedule; this is reflected in Section 2.3. The schedule was presented at the Preliminary Design Review and periodically reviewed at team meetings to establish and maintain *stakeholder* commitment.

2.2 Budget

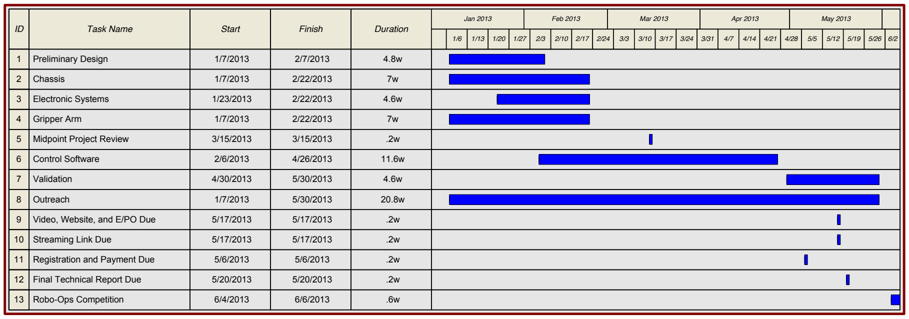
The project budget was projected to be $16,000 based on projected travel and fabrication expenses. Funding for the budget was received through generous sponsorships from the NASA WV Space Grant Consortium, the WVU Benjamin M. Statler College of Engineering and Mineral Resources and the Lane Department of Computer Science and Electrical Engineering, as well as the stipend received from NASA/NIA. The budget covers all costs associated with 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).

WVU Mars Rover Budget Overview		
	Funding	Expenses
Sponsors and Fundraising	**16,000**	
Mechanical Parts		6,500
Electronics		4,000
Travel & Registration		5,500
TOTAL EXPENSE		**16,000**

Table 1: Budget Overview

2.3 Schedule

The schedule was developed and tracked using a Gantt chart. A project schedule, Figure 2, was developed through analysis of the WBS, the team's capabilities, and the 19-week period between project inception and departure for the competition. The schedule identifies the competition milestones, major reviews, and deliverables with associated subtasks and tests.



ID	Task Name	Start	Finish	Duration
1	Preliminary Design	1/7/2013	2/7/2013	4.8w
2	Chassis	1/7/2013	2/22/2013	7w
3	Electronic Systems	1/23/2013	2/22/2013	4.6w
4	Gripper Arm	1/7/2013	2/22/2013	7w
5	Midpoint Project Review	3/15/2013	3/15/2013	.2w
6	Control Software	2/6/2013	4/26/2013	11.6w
7	Validation	4/30/2013	5/30/2013	4.6w
8	Outreach	1/7/2013	5/30/2013	20.8w
9	Video, Website, and E/PO Due	5/17/2013	5/17/2013	.2w
10	Streaming Link Due	5/17/2013	5/17/2013	.2w
11	Registration and Payment Due	5/6/2013	5/6/2013	.2w
12	Final Technical Report Due	5/20/2013	5/20/2013	.2w
13	Robo-Ops Competition	6/4/2013	6/6/2013	.6w

Figure 2: Milestones and major tasks

2.4 Project Lifecycle

The *incremental project lifecycle* model was chosen for this project, shown in Figure 3. This model combines the linear nature of the waterfall model with the iterative nature of the prototyping model.

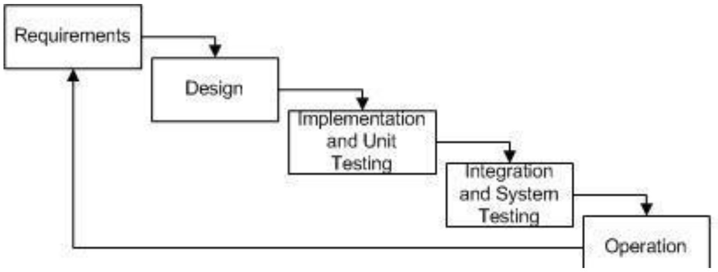


Figure 3: Incremental Model [3]

Following this approach, the product is developed in each increment following the waterfall model. Each iteration through the five stages produces a new deliverable. The first deliverable is the core product, which meets the basic requirements. Evaluation of the core product by the stakeholders leads to additional product requirements. These additional requirements are used to create a plan for the next design, fabrication, and testing increment. The process repeats until the stakeholders are satisfied and a complete product is obtained. This model is useful in that it allows for a stable development from the beginning, while allowing for changes to the requirements, provided that they do not drastically alter the core requirements [3].

2.5 Concept of Operations

The concept of operations describes the system's progression during the mission to meet objectives [4]. The mission objective of the rover is to traverse the simulated planetary surface at the JSC Rock Yard, find and collect rock specimens, and return with them to the Mars Hill starting area [5]. This requires the following core operations: locating specimen, navigating the obstacle field to the specimen location, collecting the specimen, and returning to Mars Hill at the end of the designated acquisition time. Figure 4 shows the primary concept of operations in a state diagram. Each of these operations must be executed in the order illustrated to assure mission success. The only exception is *Evaluate Time to End of Trial*; this task is done continuously and once the remaining time reaches a threshold to be determined in practice runs, the rover will start its traversal back to Mars Hill.

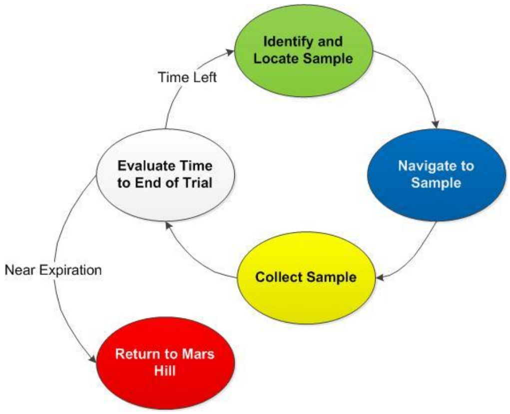


Figure 4: Concept of Operations Diagram

2.6 Requirements Definition

Requirements are the basis of design [2], as illustrated in the project lifecycle model in Figure 3. Utilizing the CMMI process area of Requirements Development (RD), the product and derived requirements were developed and analyzed during the requirements definition cycle. The RD process area requires that operational concepts and scenarios are established, as this can influence requirements [2]. The team utilized the concept of operations, detailed in Section 2.5, in conjunction with the rules and regulations set forth for the 2013 RASC-AL Exploration Robo-Ops challenge [6] to define the preliminary requirements. The requirements were captured in the System Requirements Document (SRD) per the method described in the NASA Systems Engineering Handbook [7]. The initial requirements review was held with the entire team present on January 1 2013, during the project kickoff meeting. The requirements were refined. As design decisions were made to satisfy the preliminary requirements, further requirements were derived that better defined the needs of the system. These were reviewed during the preliminary design review. As the design process progressed, requirements were constantly refined as a result of prototype creation and evaluation. Each requirement comprises an identification number (ID) for tracking, category, definition, and are further categorized as either required or objective. The categories help dictate how the requirements are tracked to validation. Physical requirements shall be validated through observation and operational testing, while power shall be validated with unit testing and monitoring, and control and communications (C^2) requirements shall be validated through unit testing. An excerpt from the SRD can be found in Table 2. The full SRD is listed in Appendix A.

Table 2: System Requirements (Excerpt)

ID	Category	Requirement	Required/ Objective
1	Physical	Robot shall fit within a 1 x 1 x 0.5 meter container	R

2.7 Risk Assessment

The Risk Management process identifies potential problems and identifies mitigation techniques to minimize negative impact on the mission [2]. The *Risk Management* (RSKM) CMMI process area defines strategies for determining risk source, categories, and management strategy [2]. Using these principles, risks were identified and classified following the preliminary design review. Continual risk management was accomplished by requiring each team member to identify risks encountered and anticipated during development. A risk management matrix was maintained that tracked risk, category, effect, and mitigation strategy. Category was derived from the consequence and likelihood per the assessment matrix in Figure 5. Consequences were based on a 1 to 5 scale with 1 being non-critical and 5 indicating a mission failure [4]. Likelihood was rated on a 1 to 5 scale with 1 being least probable and 5 indicating that the risk will certainly happen without mitigation. An excerpt from the risk management matrix is illustrated in Table 3. The full risk management matrix can be found in Appendix B.

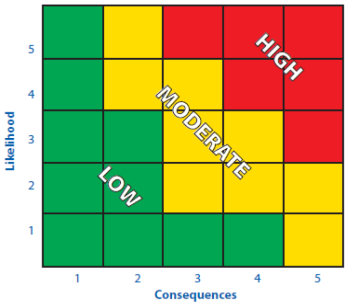


Figure 5: Risk Assessment Matrix

Table 3: Risk Management Matrix (Excerpt)

Risk	Category	Effect	Mitigation
LiPo/LiFe battery discharged below safe voltage	High	Power system fails, causing loss of drive, communications and/or excavation hardware.	Utilize control hardware to prevent over-discharge.

3 System Description

The rover is a complex system consisting of mechanical, electrical and software systems. Three primary systems were identified which comprised the robot: Drive, Sample Acquisition and Control and Communications (C^2). Division of the system in this way allowed three specialized teams to work in parallel, allowing an accelerated schedule. The drive system comprises the basic mechanical and electromechanical components necessary for rover traversal. The sensory subsystem components include Environmental Camera Array (ECA), fixed forward looking fisheye camera, and Navigation Assistance System (NAS). The power subsystem includes Lithium Polymer and Lithium Iron Phosphate batteries, an intelligent voltage regulator, and circuit protection components.

3.1 Drive System

The drive system comprises the basic mechanical and electromechanical components necessary for rover traversal. These include the chassis, sensory subsystem, and power subsystem components. The chassis includes the frame and drive elements such as motors, gearboxes, and wheels.

3.1.1 Chassis

The rover shown in Figure 6 is built upon the rocker-bogie suspension system with a bar differential. 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. Rather, it employs kinematics to maximize traction. The system is designed to evenly distribute the rover's mass across all six wheels minimizing sinking in soft and uneven ground [8]. The rocker-bogie arms are constructed from carbon fiber tubes, providing a strong, lightweight foundation. The chassis platform is fabricated using aluminum framing with vacuum formed plastic covering over a lightweight aluminum support system. This platform houses the sample acquisition system, control/communications systems, and the ECA.

Figure 6: Rocker-bogie system

Propulsion is provided by six in-wheel brushless DC motors. These motors have an added planetary gearbox to provide adequate torque while still allowing the rover to move at a pace of 3 feet per second. The rubber wheel diameter is 25 centimeters providing ample ground clearance and reliable traction, Figure 7. This ground clearance allows the rover to negotiate 12 centimeter tall obstacles per system requirements. Powerful servomechanisms, incorporating position-based control, steer the rover. The servomechanisms control the four corner-mounted wheels. This four-wheel steering design allows a near-zero turning radius, allowing the operator to easily maneuver around obstacles.

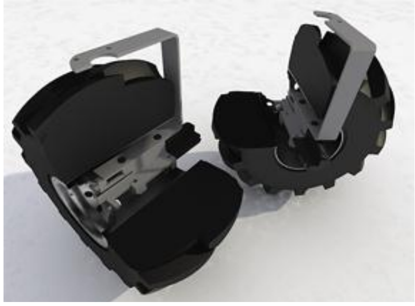


Figure 7: Rubber wheel with in-wheel brushless DC gearhead motor.

3.1.2 Sensory System

3.1.2.1 Environmental Camera Array

The ECA consists of a series of stationary cameras use to visualize the area around the robot. The ECA consists of 5 cameras, one camera will be directed toward the robot arm collection area and four cameras will be mounted on a tower facing each direction. A constant feed from the forward arm camera will be provided along with a single selectable feed from the tower camera. The resolution and frame rate of all cameras will be individually selectable via the rover interface. The capability to switch between multiple stationary cameras allows the user to switch viewing sides instantaneously. This is preferred over a Pan Tilt and Zoom camera. Figure 8 shows the ECA layout on the robot.

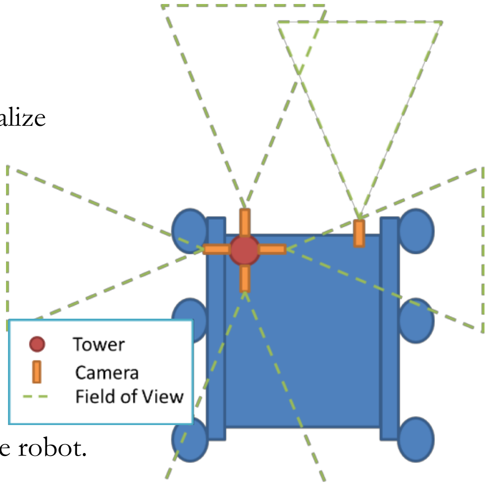


Figure 8: ECA arrangement.

3.1.2.2 Object Identification System

To improve the ability to visualize targets in the on-board cameras, a color-based OIS was implemented. The vision algorithm is performed on-board the rover using the high resolution image collected by the camera. The processed image will then be subsampled to reduce amount data transmitted. This allows the visualization of objects of interest at a further distance while simultaneously reducing the strain on communications. The sensitivity of the object detection algorithm will be remotely selectable via the robot interface. Figure 9 depicts the OCU with OIS running on the left video screen.

Figure 9: Operator Control Unit (OCU) with OIS

3.1.2.3 Navigation Assistance System

The primary navigation method for the rover is teleoperation, based on imagery transmitted from the onboard cameras. However, due to communication latency, controlling the rover in real-time is impossible. The rover employs a NAS, which provides a precise state vector including global position, three-axis velocity, and three axis altitude. This data allows the operator to know where the rover is in the operating environment as well as the goal position to be navigated to autonomously. Furthermore, the inertial data provides a means to check for wheel slippage by detecting a difference in speed reported at the wheels versus speed reported by the NAS. Testing of the NAS is shown in Figure 10.

RCU software for providing computer based control of the drive system is currently nearing completion. NAS location output will also be formatted into a Keyhole Markup Language (KML) stream, allowing the operator to view a map of the rover's travels on Google Earth. The team will determine and implement useful telemetry, providing important feedback to the operator while minimizing data to preserve bandwidth.

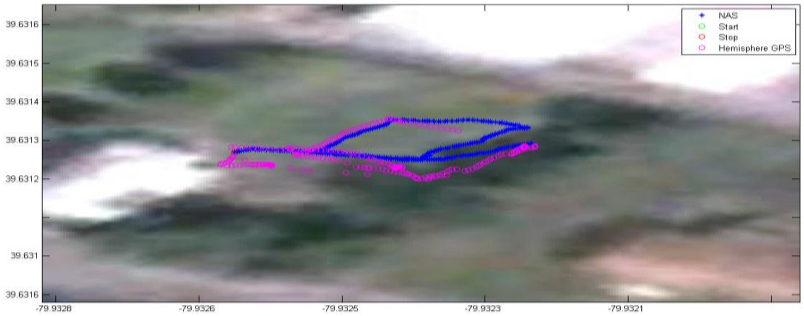


Figure 10: NAS Testing

3.1.3 Power System

The power system is designed to provide ample power for a full 60 minute competition run and isolate the power used for the motors from the control and communications components. It includes over-current protection for the control electronics and includes an external battery cutoff switch to allow for quick disconnect of power if necessary.

The power system is comprised of the batteries, motor controllers, DC-DC voltage converter, circuit protection, and emergency battery disconnect circuit. Eight Lithium Iron Phosphate and Polymer batteries are required for operation. The LiFe/LiPo batteries were chosen for their high capacity-to-weight ratio and their high discharge capabilities, allowing large currents to be drawn for short periods of time in the event of a motor stalling. Six 4.5 amp-hour (Ah), 9.9 volt (V) LiFe batteries were chosen to power each of the 6 HK120A motor controllers. A 6 Ah 12.8V LiFe battery powers the steering servos and sample acquisition arm servos. An 8 Ah capacity, 18 V LiPo battery supplies a Mini-Box DC-DC voltage converter to provide a constant voltage source to the RCU computer and other control electronics. This separate battery is required to help alleviate lengthy wirings and any inducted noise or a large current draw from the motors affecting the control or communications hardware. Figure 11 illustrates the major hardware components, major sensory interfaces, and the individual power legs.

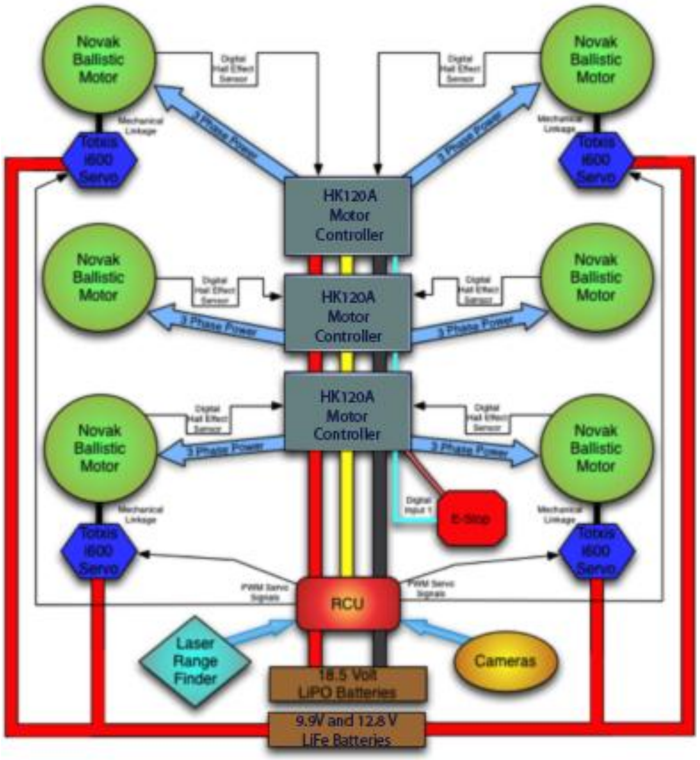


Figure 11: System Diagram

The power system also addresses two major risks. First, LiPo/LiFe batteries carry a risk of damage if over-discharged. This risk is mitigated through the use of hardware with voltage sensing capability. The HK120A motor controllers, Mini-Box DC-DC regulator, and Servo/Arm Battery all offer the ability to shutdown when the battery voltage reaches a programmable minimum, preventing over-discharge. Finally, in the event of a loss of control or catastrophic electrical fault, power to all systems can be disconnected through the press of a single emergency stop button. The negative leads from each battery share a common ground bus that is wired through an exterior battery disconnect switch.

3.2 Sample Acquisition System

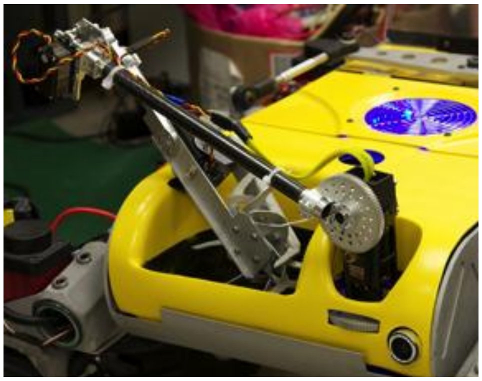


Figure 12: Sample Acquisition System

The sample acquisition system is composed of a robotic arm with a custom end effector, a camera tower with four USB webcams directed to cover a 360° viewpoint, a sample containment hopper and sophisticated control software. The robotic arm is mounted on the front face of the rover platform which is directed forward in order to collect samples located in front of the rover. The robotic arm can also be stowed diagonally across the top to minimize vibrations during transit. The imagery data from the camera system will be used as an input to the OIS which has the capabilities of determining the samples coordinates.

The sample acquisition system, Figure 12, comprises a robotic arm with a gripper, camera, collection bin, and control software. The robotic arm is mounted at the front of the rover platform facing forward in order to collect samples sitting in front of the rover. The control software will process distance information along with the joint-angles of the arm to determine a path to the object, which is used to automate the acquisition of samples.

3.2.1 Arm/Gripper/Collection bin


Figure 13: Robotic Arm and Collection bin

The robotic arm is a custom 3 Degree of Freedom manipulator designed using high torque PWM servos for each of the 3 joints and the gripper. The base servo has 180 degrees of rotation and the shoulder joint has over 270 degrees of movement. The elbow joint also has 180 degrees from rotation to allow the operator to adjust the position of the gripper. The arm has been designed to have a lifting capacity of over 0.5 kg when fully extended. Both bicep and forearm sections are fabricated from 15 mm outside diameter carbon fiber tubing to minimize structural weight while maintaining structural integrity. Figure 13 shows rendering of the robotic arm and end effector mounted on the rover.

An aluminum claw shaped gripper design incorporates a series of curved fingers on both sides which interleave when clasped together. The fingers are arranged to hold irregular shaped items of a diameter of 1.5 cm to 9 cm when closed. This design permits samples to be scooped from sand or small pebbles while most of the unwanted material is sifted out when the arm is lifted.

A collection bin is incorporated on the front of the rover for storing retrieved samples. The collection bin is constructed of a lightweight fiberglass frame shown in Figure 12. This design allows ample room to collect 30 samples of an 8 cm diameter.

3.2.2 Control Software

The control software for the robotic arm provides both manual and automated operation. Manual operation is performed using an Xbox 360 controller. The goal of automated operation mode is to reduce the level of dexterity required to operate the arm by automating as much of the sample collection process as possible. Given a Cartesian coordinate for the desired end-effector position, the software will generate an optimal combination of joint angles that will place the end-effector at the desired position. This is accomplished by modeling the arm as a kinematic chain and then utilizing an inverse-kinematics solver provided by the Orocos Kinematics and Dynamics Library (KDL) [8] .

3.3 Control and Communication Systems

The rover is controlled by two computers: the OCU and the RCU. The OCU is housed on a server at WVU. Its software is responsible for displaying video and telemetry from the rover and serializing operator input to be transmitted to the rover. The OCU is also responsible for broadcasting and recording live USTREAM video streams. The OCU is designed to be a TCP/IP Server. The OCU software listens for connections from the rover, accepts connections, and transmits commands. The OCU software also has several UDP sockets that are responsible for receiving rover imagery to minimize the bandwidth used.

The RCU computer resides on the rover 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 OCU and RCU are linked by a communications system incorporating a wireless broadband modem. Figure 14 shows the communications relationship between the OCU and RCU. The RCU is designed as a TCP/IP client that will continuously attempt to connect to the OCU if a loss-communication-disconnect were to occur.

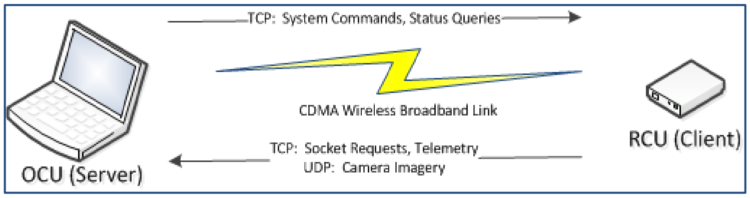


Figure 14: Communications Diagram for OCU/RCU

3.3.1 RCU Computer

The 'brain' of the RCU is the onboard computer. It receives and dispatches operator commands, interfaces to the robot's subsystems, processes video from all cameras, and performs autonomous macros to aid the operators in driving the robot, navigating the Rock Yard, and operating the sample acquisition arm.

The components for the RCU computer were chosen for reliability and performance. The CPU selected is a dual-core 2.7 GHz Intel i5-23890T low-power-consumption processor. The i5 has a thermal design power (TDP) of 35W and also provides significant computing capability with a 2.7 GHz clock speed and Intel's Hyperthreading technology for a total of 4 threads [9]. The board supports 2 serial connections through the use of a Jetway 2-port RS-232 Mini-PCIe module. The centralized motor controller utilizes serial communications for their high reliability. A Solid-State Drive (SSD) serves as the primary storage. The absence of moving parts makes the SSD more resilient to vibration and impact than hard disc drives [10].

3.3.2 Motor Controllers

A centralized Lynxmotion motor controller is used to produce PWM signals to power each of the 4 arm servos and send control signals to each of the 6 HK120A controllers for in the wheel motors. The HK120A brushless DC motor controllers were chosen to control the rover's six motors. These sensored motor controllers provide closed-loop motor control utilizing the Hall-effect sensors in each wheel. Each wheel is individually powered allowing a level of redundancy; if one wheel/or channel fails the other 5 can continue to propel the rover in the degraded state. This is similar to what happened to the NASA *Spirit* when one of its wheels failed in 2006 [11], yet it was able to continue its mission for over 3 years after the failure [12].

3.3.3 OCU Control Hardware

The hardware for the OCU is comprised of three components: a server on the WVU network and two USB-connected Xbox 360 controllers. The server has a graphics card capable of running two monitors to give the rover and arm operators their own displays.

3.3.4 Control and Communications Software

The communications system is crucial for proper teleoperation of the rover from the remote site on WVU's campus. The communications link utilizes a virtual private network (VPN) server whereas the OCU and RCU will connect to the same virtual network, allowing them to communicate directly with one another. This assists with troubleshooting by making possible the option of using a remote desktop client for remote access.

Both the RCU and OCU software have been designed to be flexible, safe, and reliable. Flexibility is achieved through the use of object-oriented design. The architecture is easily adaptable to modifications of the hardware configuration, such as changes in joystick controllers, motor controllers or wiring. These changes need only be reflected in an XML-based configuration file, and no recompilation is necessary. The RCU software implements a multi-threaded design to be more robust to failure and multiple watchdog timers to avoid erratic and/or unsafe behavior.

3.3.5 Network Communication Software

The competition rules dictate that teleoperation must be performed using a Verizon wireless broadband card and controlling the rover from the West Virginia University campus. Utilizing this type of network communication gives two options for socket-based communication: TCP or UDP. TCP is a connection-oriented protocol, in which two devices communicate between each other using a handshaking procedure. The handshaking procedure enables synchronization between the devices and methodology to request re-transmission of lost packet data to prevent data loss. UDP is a connectionless protocol without any handshaking procedure. The lack of handshaking is faster, but doesn't provide any data loss prevention.

Any data being transmitted from the rover (RCU) to the OCU is sent using UDP for these reasons:

1. It is not critical that every pack of telemetry data (GPS coordinates, compass heading, etc) reach the OCU. If a packet of telemetry gets lost it will simply be replaced with more up-to-date data.
2. Video camera MJPEG frames are transmitted most efficiently using UDP. For the same reason mentioned in number one, if a single frame is lost it will simply be replaced with a newer frame.
3. Any unsolicited communications, such as transmitting of GPS telemetry and imagery, must be sent via UDP from the rover due to the limitations of the cellular wireless.

Rover commands from OCU to RCU, such as camera control and rover movement, are sent via a TCP link. The RCU server is a TCP/IP client that constantly connects to the OCU TCP/IP server. Once the connection has been established commands can be transmitted directly to the RCU from the OCU. This TCP/IP connection effectively opens a "tunnel" between the OCU and RCU that allows commands to be sent directly through the wireless firewalls and NAT.

Control of the bandwidth usage is provided by user-adjustable parameters for video and telemetry. The rate at which the RCU sends telemetry and video updates, as well as the video quality, is adjustable on the fly. This dynamic capability provides maximum control over the distribution of bandwidth to allow for optimal balance depending on the network performance and the task at hand.

3.3.6 RCU Software

The RCU software is responsible for motor control, multiple camera control and image acquisition, broadcasting telemetry to the OCU, and accepting commands from the OCU. The software is a heavily multi-threaded environment to provide optimal performance and interaction between each software component. The use of separate threads to handle operation of each individual component allows all of the components, which may operate at different update frequencies, to function harmoniously. The division of work amongst these classes and threads sandboxes each component from the others, ensuring that the failure of a single one does not adversely affect the rest of the system. This way, a non-essential component could fail, but the rest of the rover can continue operation.

Safety mechanisms are implemented with watchdog timers in the device controller layer. This provides each controller its own timeout policy and enforcement procedures, and isolates the task of from the communications system. The OCU and RCU maintain a heartbeat system so the RCU does not continue operating under loss of the OCU. A timeout between the OCU and RCU will cause rover motion to cease by triggering the independent timeout policies for each motor controller.

Rover telemetry includes GPS/IMU fused and filtered data, digital compass data that includes roll, pitch, and heading, and battery voltage levels. All telemetry software classes implement an interface titled IProvideTelemetry. This interface specifies the "contract" that telemetry classes must adhere to so that they can be easily integrated into the RCU software. This object-oriented mechanism is used so that any future sensors can simply implement the IProvideTelemetry interface and then be added to the RCU software.

Each telemetry device is implemented in its own class with its own data acquisition thread. For serial devices, the SerialPort_DataReceived event is used to capture all data and inserted into a queue. Then, a background worker thread is responsible for dequeuing the data and raising a TelemetryUpdated_Event. This event is part of the IProvideTelemetry interface contract and is required to be implemented.

The RCU packages all telemetry into a single packet which is serialized and transmitted via UDP to the OCU. To compensate for various update rates from different sensors, the IProvideTelemetry interface requires that device classes (e.g., GPS, compass) provide a mechanism for the user of the class to specify how often they want telemetry data provided via the Telemetry Updated_Event. For example, telemetry devices will almost always provide data at different rate; a typical GPS updates at 20Hz, a digital compass at 10Hz, and analog-to-digital battery values at 1 Hz. To handle this difference in update rates and provide a means to package all telemetry into a single packet, the user of each class will specify how often they want updated telemetry. For the RASC-AL competition, it is not necessary to transmit telemetry data faster than once a second, so these devices are instructed to raise their TelemetryUpdated_Event once every two seconds (as an example). The background thread is always processing data thus ensuring that telemetry is not stale when reported.

Webcam imageries are acquired by integrating the AForge library into the RCU software. AForge is an open source set of libraries for incorporating robotic techniques such as computer vision, artificial intelligence, and image processing into robotic software [13]. This library provides a simple interface to capture individual frames from the video sources. To minimize bandwidth use, the frames captured from the cameras are compressed and transmitted in JPEG format. The level of compression and frame rate can be varied dynamically to provide the best balance for the current task.

3.3.7 OCU Control Software

The operator control unit software has two main tasks: process user input to control the state of the rover and display telemetry feedback from the RCU. The OCU is designed for two operators: the rover operator and the sample acquisition system operator. Each has their own user interface and work in concert with each other to achieve mission objectives.

The rover operator can control the rover with an Xbox 360 controller, adjust network parameters (IP endpoint, communication rate), adjust controller settings (joystick sensitivity), and also select individual types of telemetry (video feed, position information, battery voltages) to display to their preference. The rover operator also has a Google Earth display that shows the rover's current position, heading, and previous path of travel overlaid on satellite imagery of the JSC Rock Yard shown in Figure 15.

Figure 15: Example of rover tracking using Google Earth

The sample acquisition operator can operate the robotic arm, set trajectories to sample locations with an Xbox 360 controller as well as adjust controller settings (joystick sensitivity). The arm GUI shows the arm camera view to allow for precise maneuvering.

A key feature of the OCU software is the ability to vary the quality and update frequency of the video feeds from each camera. Given the restricted bandwidth, balancing the quality of the images versus the frequency of transmission will be a crucial, and often-changing, element of operation. The user is able to change these parameters with minimal effort using controls built directly into the OCU software, as shown in Figure 16. Any changes are then forwarded to the RCU and immediately enacted. This allows the operators to improve image quality when fine

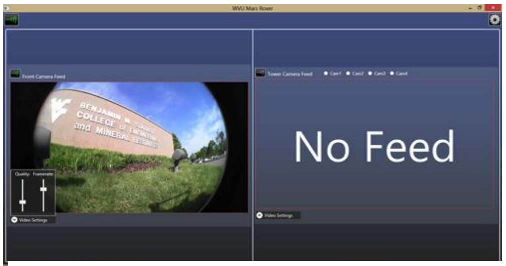


Figure 16: OCU software demonstrating dynamic adjustment of video parameters

detail is needed, such as when searching and acquiring samples. Conversely, the quality can be dropped and the frequency increased when a smoother image feed is desired, such as when driving the rover.

4 Verification and Validation

In order to ensure that the rover would be competitive, all requirements defined in the requirements definition needed to be met. Verification, the process ensuring that “selected work products meet their specified 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. The verification process began with the Preliminary Design Review, ensuring that the system design met the defined requirements. Early verification processes included CAD modeling of key components, subsequent assembly of a fully functioning CAD model of the robot, and extensive calculations to verify that components selected for the rover would meet or exceed system requirements. Once the CAD models and component selections were vetted, mechanical prototypes were fabricated for testing of the drive system under load; evaluation of the sample acquisition capabilities; and testing of the communications over the CDMA wireless modem connection. As system components were assembled, physical requirements were checked by observation to ensure that the rover being built would meet size and mass requirements. As systems became operational, unit tests were performed to check accordance with power and C^2 requirements.

The communications framework software has been thoroughly validated to ensure that communications between the operators and the rover will be robust and reliable. Testing has focused on the latency, throughput, and behavior of the wireless modem in various scenarios of rover system design. The primary data transmitted on the communications channel will be TCP command packets and camera imagery. Latency for imagery was consistent at approximately one second; this was observed during a good 4G signal (3 bars). Throughput testing resulted in a 0.55Mbps download and 0.35 upload rate. This is almost identical to that reported for the Verizon 3G/4G performance in Houston, indicating that the performance should not change dramatically when the rover is deployed at JSC.

Degraded communications testing has been performed to evaluate the robustness of the software. Testing conditions included very poor 3G service and 1xRTT (approximately 0.15 Mbps) service. Because the RCU software is a TCP Client, it is responsible for always maintaining a communications link to the OCU server. This testing has demonstrated that if the communications fail, the RCU will repeatedly attempt to connect to the OCU automatically.

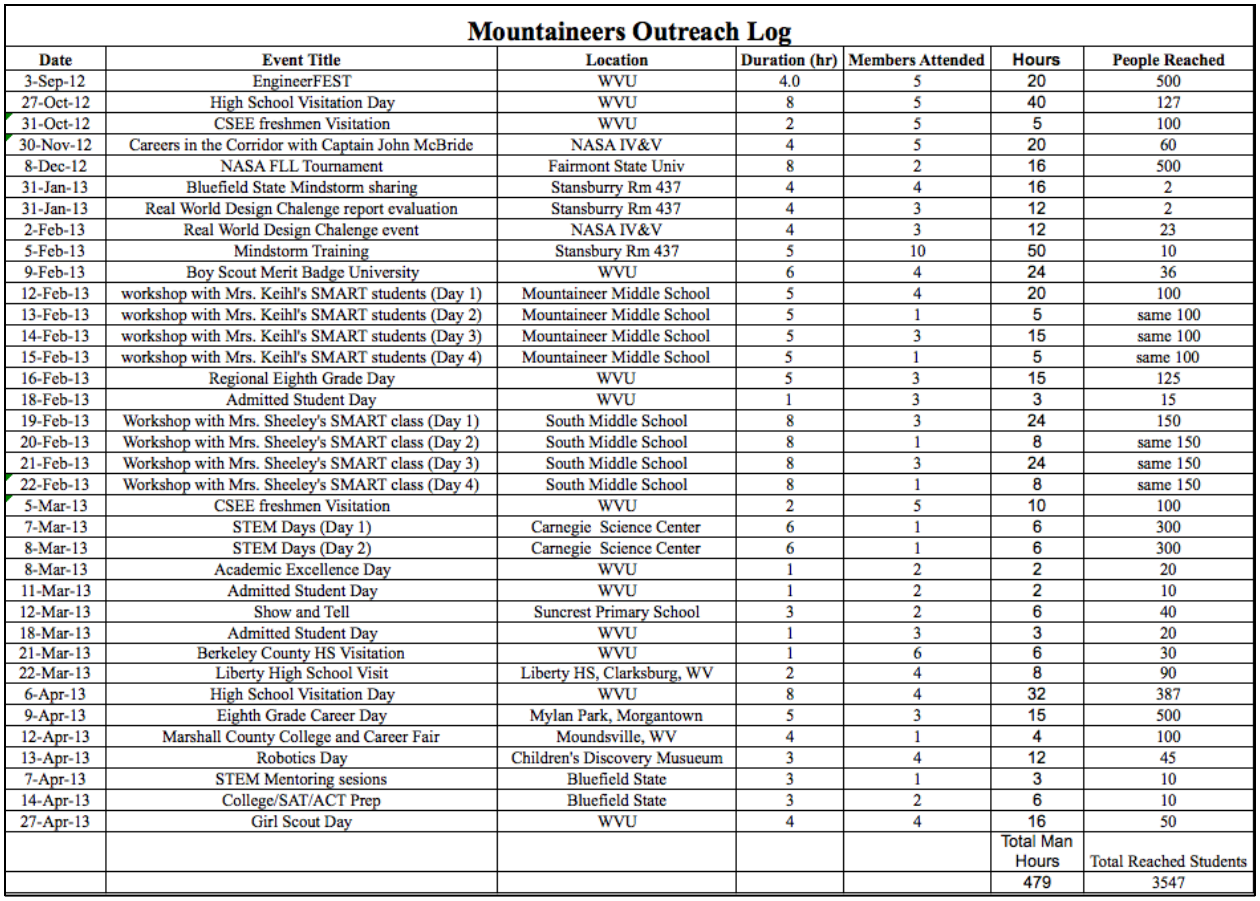
The rover, with full payload, was tested in the environments listed in the project requirements: rocks, sand, and a 33% grade. The rover was able to make multiple consecutive traversals across a 12 ft. sandbox, overcome a 10 cm rock, and ascend and descend a rocky 30% grade. All of these tests were carried out with the operators quarantined in the server room, operating off of rover video. The NAS has been independently tested and has demonstrated heading accuracy within 2 degrees and acceptable GPS accuracy.

5 Education and Public Outreach

Community outreach is an important part of the NASA-NIA RASC-AL Exploration Robo-Ops Competition that the team did not take lightly. This year the Mountaineers combined outreach efforts with team members from Bluefield State College. Together the groups were able to reach more students by dividing their impact to both the northern and southern parts of West Virginia.

The Mountaineers were aware that their state’s schools have consistently ranked far below the national average in science and math standardized testing. In 2011, West Virginia public schools ranked 46th out of the 50 states in the science, technology, engineering and mathematics (STEM) subjects. The purpose of the Mountaineers' outreach projects was to expose young students to the opportunities in STEM fields and educate them on careers in these fields. In order to reach these goals, the Mountaineers underwent necessary training from the NASA Independent Verification and Validation (IV&V) Educator Resource Center (ERC), allowing team members to become certified educators. With this training, the Mountaineers supplemented the curriculum of two Monongalia County Middle Schools using Lego Mindstorms robotic educational kits.

The Mountaineers also planned a variety of their own workshops, designed for several different age groups, that utilize robotics to encapsulate some of the most exciting aspects of the STEM fields. The team tracked all of their events in the Outreach Log located in Figure 17. In all, the Mountaineers dedicated 479 man-hours towards influencing over 3,500 students and promoting the STEM initiative throughout the great state of West Virginia. Selected events are highlighted in the following paragraphs.



Mountaineers Outreach Log

Date	Event Title	Location	Duration (hr)	Members Attended	Hours	People Reached
3-Sep-12	EngineerFEST	WVU	4.0	5	20	500
27-Oct-12	High School Visitation Day	WVU	8	5	40	127
31-Oct-12	CSEE freshmen Visitation	WVU	2	5	5	100
30-Nov-12	Careers in the Corridor with Captain John McBride	NASA IV&V	4	5	20	60
8-Dec-12	NASA FLL Tournament	Fairmont State Univ	8	2	16	500
31-Jan-13	Bluefield State Mindstorm sharing	Stansburry Rm 437	4	4	16	2
31-Jan-13	Real World Design Chalenge report evaluation	Stansburry Rm 437	4	3	12	2
2-Feb-13	Real World Design Chalenge event	NASA IV&V	4	3	12	23
5-Feb-13	Mindstorm Training	Stansbury Rm 437	5	10	50	10
9-Feb-13	Boy Scout Merit Badge University	WVU	6	4	24	36
12-Feb-13	workshop with Mrs. Keihl's SMART students (Day 1)	Mountaineer Middle School	5	4	20	100
13-Feb-13	workshop with Mrs. Keihl's SMART students (Day 2)	Mountaineer Middle School	5	1	5	same 100
14-Feb-13	workshop with Mrs. Keihl's SMART students (Day 3)	Mountaineer Middle School	5	3	15	same 100
15-Feb-13	workshop with Mrs. Keihl's SMART students (Day 4)	Mountaineer Middle School	5	1	5	same 100
16-Feb-13	Regional Eighth Grade Day	WVU	5	3	15	125
18-Feb-13	Admitted Student Day	WVU	1	3	3	15
19-Feb-13	Workshop with Mrs. Sheeley's SMART class (Day 1)	South Middle School	8	3	24	150
20-Feb-13	Workshop with Mrs. Sheeley's SMART class (Day 2)	South Middle School	8	1	8	same 150
21-Feb-13	Workshop with Mrs. Sheeley's SMART class (Day 3)	South Middle School	8	3	24	same 150
22-Feb-13	Workshop with Mrs. Sheeley's SMART class (Day 4)	South Middle School	8	1	8	same 150
5-Mar-13	CSEE freshmen Visitation	WVU	2	5	10	100
7-Mar-13	STEM Days (Day 1)	Carnegie Science Center	6	1	6	300
8-Mar-13	STEM Days (Day 2)	Carnegie Science Center	6	1	6	300
8-Mar-13	Academic Excellence Day	WVU	1	2	2	20
11-Mar-13	Admitted Student Day	WVU	1	2	2	10
12-Mar-13	Show and Tell	Suncrest Primary School	3	2	6	40
18-Mar-13	Admitted Student Day	WVU	1	3	3	20
21-Mar-13	Berkeley County HS Visitation	WVU	1	6	6	30
22-Mar-13	Liberty High School Visit	Liberty HS, Clarksburg, WV	2	4	8	90
6-Apr-13	High School Visitation Day	WVU	8	4	32	387
9-Apr-13	Eighth Grade Career Day	Mylan Park, Morgantown	5	3	15	500
12-Apr-13	Marshall County College and Career Fair	Moundsville, WV	4	1	4	100
13-Apr-13	Robotics Day	Children's Discovery Musueum	3	4	12	45
7-Apr-13	STEM Mentoring sesions	Bluefield State	3	1	3	10
14-Apr-13	College/SAT/ACT Prep	Bluefield State	3	2	6	10
27-Apr-13	Girl Scout Day	WVU	4	4	16	50
					Total Man Hours	Total Reached Students
					479	3547

Figure 17: The Mountaineers Outreach Log

5.1 STEM in Schools

The Mountaineers believe that middle school students would receive the greatest impact from the team's involvement. The team contacted the gifted class directors, Mrs. Keihl of Mountaineer Middle School and Mrs. Sheeley of South Middle School. The Mountaineers specifically sought out gifted students because they have available time during the school day to expand their academic horizons. These teachers were able to help the team schedule a four-day Mindstorm robot workshop for the Spring 2013 and were excited by the opportunity being provided to their students.

In previous years, the Mountaineers have used Lego Mindstorm NXTs for small scale prototyping. The Mountaineers found these kits to be a useful tool and believe they could be used to engage younger students. Through the team's contacts at the NASA IV&V ERC, it was determined that 10 educational kits were readily available to certified educators. These kits consisted of a laptop computer and a Lego Mindstorm NXT. On February 5th, members of the Mountaineers team were trained by the NASA IV&V ERC and became certified to teach Mindstorm workshops.

The Mountaineers taught separate four-day Mindstorm workshops at two different local middle schools. The first was taught to six gifted classes at Mountaineer Middle School, reaching 120 total students. The second four-day workshop was taught to nine gifted classes at South Middle School, reaching another 150 students. During the first day, the basics of the Mindstorm robots and the NXT software were taught, such as how to program the robot to move backwards and forwards, determine distance, and turn a specified number of degrees. The second day challenged the students to program the robots to navigate through a maze using what they had previously learned. On the third day, the Mountaineers taught the students to autonomously maneuver the robot through mazes using sonar, light, and touch sensors. During the fourth day, the students were given the entire class period to refine their autonomous maze solving program from the third day. At the end of the last day, the mountaineers talked to the student about the importance of going to college and pursuing a degree in any of the STEM fields. Figure 18 below show the participation and thank you letter from the students.

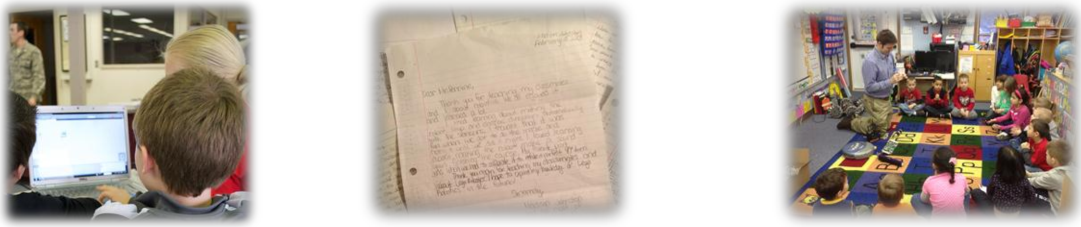


Figure 18: Team member interacts with the students to program their Mindstorm Robots

5.2 Robot Demonstration

The Mountaineers were contacted by Nancy Kincaid of Suncrest Primary School. Mrs. Kincaid had spoken with several teachers who had spoken highly of the Mindstorm workshops performed by the team. She had curriculum in place to introduce her students to the world of robotics with Lego WeDo robotic kits. She found the Mountaineers' Facebook page and contacted the team. As a preface to this curriculum, she asked the Mountaineers team to visit with the students and display exciting robots to the kids, Figure 19. The team was excited for the opportunity and scheduled a robot demo with two classes at Suncrest Primary School. The kids loved the hands on workshop, enjoyed interacting with the robots, and were very excited to build their own.

Figure 19: Students play with a Sony AIBO

5.3 Bluefield State Outreach

This year, the WVU team partnered with Bluefield State College to expand its outreach program. By incorporating Bluefield into the outreach plan, a larger audience in the southern portion of the state could be reached to further diversify the outreach efforts. The students involved were Sasha Richmond and Samuel Dennah, two members of the Emerging Leaders Institute (ELI) at Bluefield State.

Sasha and Samuel came to Morgantown to be certified for teaching using the Mindstorm kits. At the end of their training, Sasha and Samuel were prepared to expand the Mountaineers' outreach efforts to the southern part of the state. They were provided with two Mindstorm kits to take with them to use in their events. The ELI mentored ten Bluefield high school students, using robotics as a method of STEM instruction. They introduced the kits at their first event, which was a college preparatory course. Using the methods defined in their training, Sasha and Samuel will mentor these students weekly until June and teach them more about robotics and programming each week. Figure 20 depicts ELI and BHS students and the college prep event.

Figure 20: ELI and BHS students at the college prep events

5.4 First Lego League (FFL) Robotics Tournament

The First Lego League is a NASA Classroom of the Future program directed by Meri Cummings. This year's FFL State tournament was held at Fairmont State University and was sponsored by the West Virginia NASA Space Grant Consortium (WVSGC). The First Lego League is a competition where middle school students can be introduced to the concepts of robotics and be exposed to the foundations of the STEM disciplines. The Mountaineers were asked to participate by WVSGC due to their training, prior experience with Mindstorm robots, and their commitment to outreach events. Several team members also participated as judges in the scrimmage held at WVU and sponsored by the Morgantown Area RoboticS (MARS).

Two members of the Mountaineer team served as referees in the event, Figure 21. Their job was to ensure fairness of the competition while also putting the kids at ease, allowing them to have fun in the competitive atmosphere. It was important to allow the participants to learn in a positive environment and watch their hard work pay off. Fifty-four teams from all over the state of West Virginia participated in the FFL tournament, totaling more than 500 students aged 9-14 years old. The team enjoyed the opportunity to support the tournament and impact such a large group of students.

Figure 21: Team members judging the event

5.5 Real World Design Challenge

The Mountaineer team was contacted by Todd Ensign, the Educator Resource Center Program Manager at the NASA IV&V. He had worked with the Mountaineers during the First Lego League competition and was aware of their commitment to outreach. He asked the Mountaineers for some assistance on a statewide competition and needed four members to be judges in the Real World Design Challenge (RWDC). The RWDC is an annual competition that provides high school students with an opportunity to form an engineering team and work on real world problems. The challenge this year was to design an unmanned aircraft system with CAD software and test it in a virtual wind tunnel. Prior to the competition, teams presented their analysis in a technical report and during the competition teams gave a presentation on their findings. The Mountaineers graded the technical reports and presentations. The winner of the competition was Cabell Midland High School. The Mountaineers established a friendship with the Cabell Midland High School team, and continue to assist them on their way to the national competition.

5.6 EngineerFEST

The transition from high school to a large university like WVU can be challenging for many students. Therefore, at the beginning of every fall semester, the Statler College of Engineering and Mineral Resources (BMSCEMR) at WVU holds EngineerFEST to introduce the new students to the engineering student organizations. The Mountaineers presented their past work and future ideas to spark the interest of new freshmen, and give the students information on how to join the program. The team spoke with several promising young engineers and excited them about the possibilities of working on the Mountaineers team in the future.

5.7 Carnegie Science Center STEM Days

The Mountaineers also took outreach projects north to Pittsburgh, PA. The Carnegie Science Center hosted a two day STEM event at which the Mountaineers were set up a table. This allowed team members to interact with students from all over southwestern Pennsylvania, and wide variety of students from both rural and urban schools were in attendance. Other universities, companies, and STEM organizations were present to engage the students and interest them in science and technology.

While the Mountaineers showcased their robots, the Statler College of Engineering and Mineral Resources was present to demonstrate the principles of biometric systems and cybersecurity using an iris scanner. This dual outreach approach was able to attract many students, as well as other curious Science Center patrons. Fortunately, the Mountaineers were stationed on the same floor of the Science Center as their robotics exhibit, which featured applications of robotics in everyday life and included everything from sorting pharmaceutical prescriptions to playing basketball. The team was able to incorporate these exhibits into their discussions with the students and relate those concepts to the RASC-AL Exploration Robo-Op competition.

5.8 High School Visitation Days

The Statler College of Engineering and Mineral Resources invited the Mountaineers to attend two "High School Visitation Days" at West Virginia University. This event is for high school students who are considering attending WVU to visit campus, interact with current students, and learn about classes and student activities.

This event provided the team the opportunity to interact with a large variety of students from many areas of the country. As with previous outreach events performed by the WVU Team, the focus was on informing the students of the opportunities available in the areas of STEM through the use of robotics. The Mountaineers presented their experiences and opportunities as students at WVU, Figure 22. They discussed the NASA/NIA Competitions and the opportunities available to them both through NASA and through WVU.

Figure 22: High School Visitation day

5.9 8th Grade Career Day of Monongalia County

On Tuesday, April 9, the Mountaineers attended the Monongalia County Eighth Grade Career Day to assist the West Virginia Space Grant Consortium. Eighth grade students from all over the county were present to see what was possible for their future and to learn how to prepare for success. Since West Virginia University is located in Monongalia County, the Mountaineers were excited to share their passion for robotics with local students. The career fair was one of the largest outreach events to date, reaching approximately 500 students, Figure 23. The Mountaineers brought examples of their past robotics projects, including a Mars Rover and Mecanum wheeled robot. Luna Bot even got wheels and greeted the fair goers. The WVSGC booth was popular and always packed with students, due in part to the several robots present and the Van de Graaff generator provided by the WVSGC. All of the students were happy to see the exciting possibilities present in STEM fields.

Figure 23: Mountaineers at the 8th Grade career day

5.10 Summary of Team Mountaineers EPO

The Mountaineers worked hard to reach as many students as possible this year. Building on past experience allowed the team to polish their presentations and techniques, engage the students more effectively, and hold events in new areas. The team was excited to work on such a variety of projects. The Mountaineers were able to reach over 3,500 different students in a wide variety of areas and age groups. Bluefield State was an invaluable resource to us as they took our outreach to previously untouched areas. The team was happy to provide them experience and materials they required. The uplifting experiences and insights gained were worth the large investment of time and energy.

6 Conclusions

The team has successfully built and tested a fully operational planetary rover that meets the requirements laid out by the stakeholders. Upon arrival at the JSC the team is confident that the WVU Mars Rover will meet and exceed the expectations set for the competiton.

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Appendix A: System Requirements Document

ID	Category	Requirement	Required/ Objective
1	Physical	Robot shall fit within a 1 x 1 x 0.5 meter container	R
2	Physical	Rover should take less than 30 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 shall traverse obstacles 10 cm in height	R
6	Operational	Rover shall ascend and descend slopes up to 33% grade (18.26 degrees)	R
7	Operational	Rover shall pick up rocks 2 - 8 cm in diameter and mass ranging from 20-150 grams	R
8	Operational	Rover shall transport at least 5 rocks of 150g mass, 8 cm diameter	R
9	Operational	Rover should transport at least 30 rocks of 150g mass, 8 cm diameter	O
10	Operational	Rover shall identify the colors red, purple, blue, green, yellow, orange	R
11	Operational	Rover shall traverse sand for distances exceeding 20 feet	R
12	Operational	Rover shall operate for 1 hour on battery power	R
13	Operational	Rover shall supply all necessary data for operation including, but not limited to video, sensor feedback, GPS	R
14	C^2	Rover shall communicate via Verizon Broadband Card	R
15	C^2	Rover shall be controlled from the WVU campus while operating at Johnson Space Center	R
16	C^2	Rover shall be controllable with a data rate of 0.6 MB download, 0.4 MB upload and data transmission latency of 300 ms	R

Appendix B: Risk Management Matrix

Risk	Category	Effect	Mitigation
LiPo/LiFe battery discharged below safe voltage	High	Power system fails, causing loss of drive, communications and/or excavation hardware.	Utilize control hardware to prevent over-discharge.
Control or communications power failure	High	If power fails to this system, control of the rover will be lost, rendering it useless and unsafe if motors are in on state.	Utilize separate battery, ensure total draw does not exceed 9A (10A fuse). Use high quality DCDC converter. Ensure motors stop if control is lost using watchdog timer.
Camera Fails	Moderate	If any of the camera fail it can hinder the operability of the rover	Use multiple cameras to provide redundancy, If one fails, continue with the others in degraded state
Arm Servo Fails	Moderate	If an arm servo fails the arm may be rendered inoperable and not be able to acquire samples	Use multiple servos at high-torque joints so that arm may be able to continue to pick up lighter samples. Monitor load on each servo and drop samples that may exceed capability
Wheel drive motor failure	Low	If a motor fails, the attached wheel cannot propel the system. This can reduce the lifetime of the remaining motors and gearboxes since they have to work harder.	Utilize independent drive on each wheel so that if 1 fails the other 5 can still propel the system in a degraded state.
NAS fails	Low	If the NAS fails rover tracking and assisted movements will not be available	Operate on vision only in degraded mode, use visual keys to identify where rover has been and hand-log