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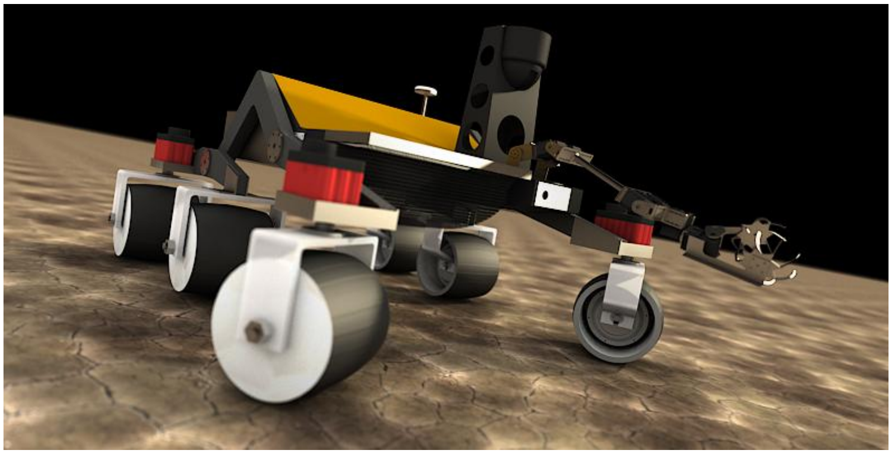

NASA/NIA RASC-AL Exploration Robo-Ops Competition Final Report

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1 Introduction

The 2012 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 include the public through the project development by posting updates to social media sites, hosting 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 both courses, cadets from Air Force ROTC Detachment 915, and a senior design team focusing on the rocker-bogie chassis design. 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 construction, six-wheel independent drive, four-wheel steering, and rocker-bogie suspension; it can be seen in Figure 1. It incorporates a Navigation Assistance System (NAS) that increases navigation precision and provides useful feedback about the mission environment to the operator. The rover houses a sample acquisition system comprising a 5 degree-of-freedom arm with laser rangefinder and camera installed to assist the operator to collect samples. 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 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, Sample Acquisition, and Control and Communications (C^2). 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 2011 semester. Initial requirements analysis lead to a preliminary design presented in our project proposal. The project kicked off upon reward of a competition spot on December 19, 2011 and the development of the proposed design commenced in January 2012. 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.

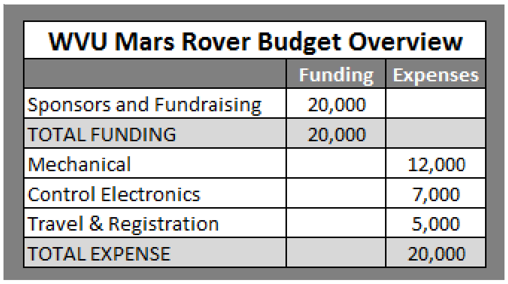
2.1 Project Scope

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 $20,000 based on projected travel and fabrication expenses. Funding for the budget was received through generous sponsorships from the NASA WV Space Grant Consortium and the WVU Benjamin M. Statler College of Engineering and Mineral Resources, 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. The full budget balance sheet is shown in Appendix A. All fabrication expenditures were tracked by the faculty advisors and the team's Chief Financial Officer (CFO).

Table 1 Budget Overview



WVU Mars Rover Budget Overview

	Funding	Expenses
Sponsors and Fundraising	20,000	
TOTAL FUNDING	20,000	
Mechanical		12,000
Control Electronics		7,000
Travel & Registration		5,000
TOTAL EXPENSE		20,000

2.3 Schedule

A project schedule 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. The schedule was developed and tracked using a Gantt chart. A condensed version of the schedule, identifying milestones and major tasks is shown in Figure 2. The full schedule is shown in Appendix B.

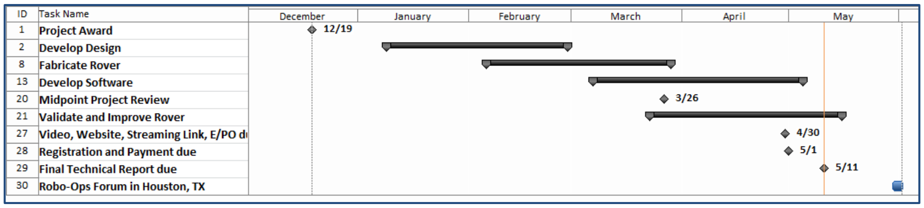


Figure 2: Schedule Overview

2.4 Project Lifecycle

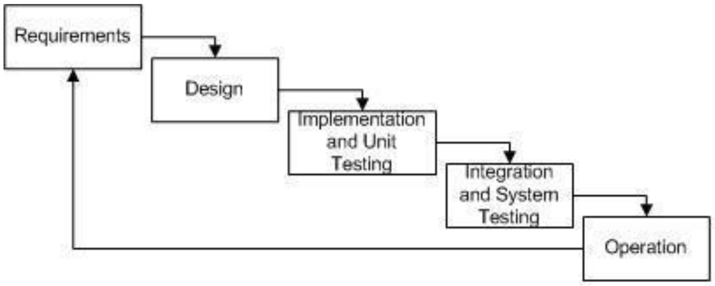


Figure 3: Incremental Model [3]

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. 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 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 operation 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: locate sample, navigate the planetary surface to the sample location, collect the sample, and return 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 in order for mission success. The only exception is *Evaluate Time to End of Trial*; this task is performed 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.

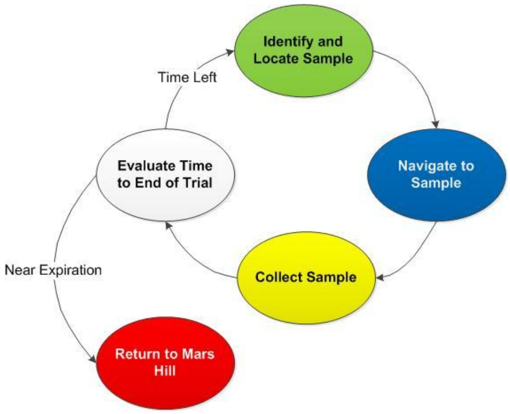


Figure 4: Concept of Operations Diagram

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 Requirements Development (RD), 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 2012 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 [7]. The initial requirements review was held with the entire team present on January 9, 2012, during the project kickoff meeting. The requirements and proposed design were reviewed and 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 dictate how the requirement is tracked to validation. Physical requirements shall be validated through observation and operational testing, 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 C.

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 proposes 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 likely 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 D.

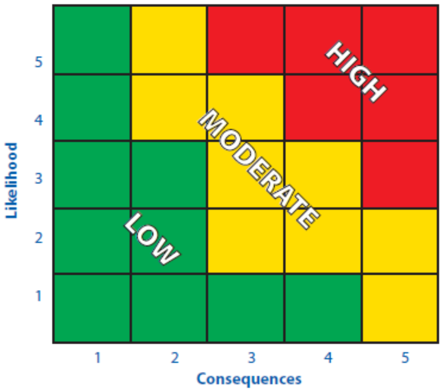


Figure 5: Risk Assessment Matrix

Table 3: Risk Management Matrix (Excerpt)

Risk	Category	Effect	Mitigation
Lithium Polymer 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 a Pan-Tilt-Zoom camera, fixed forward looking camera, scanning laser rangefinder, and Navigation Assistance System (NAS). The power subsystem includes Lithium Polymer 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. Each component of the drive system is described in Sections 3.1.1 - 3.1.3.

3.1.1 Chassis

The WVU rover employs a rocker-bogie suspension system with six independently driven wheels as the foundation of its drive system. The rover is built upon a chassis featuring a rocker-bogie suspension system. The chassis has six individually driven wheels and four-wheel steering. 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. 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 system comprises a differential, rocker, and bogie arms. The differential is custom-built using miter gears that transmit motion using a 1:1 gear ratio, the gears are assembled so that the two sides of the differential have opposite hands of rotations, similar to the rocker-bogie systems used on NASA rovers

Spirit and *Opportunity* [8]. The differential is built to allow ample range of movement between the rocker arms on either side of the chassis, allowing one side to traverse over 10 cm obstacles while the other side can stay fixed on the ground. The rocker arms are joined to the differential by aluminum torque tubes. The rockers and bogies are both constructed from carbon fiber reinforced plywood, providing a strong, lightweight foundation. Figure 6 shows the design of both the rocker and bogie components of the rocker-bogie arms. The arms house mounts for the steering servos and wheel assemblies. The assemblies have been verified, through Finite Element Analysis (FEA) modeling, to safely handle the rover load. A sample FEA model to analyze combined top and side load on the wheel mount is shown in Figure 7.

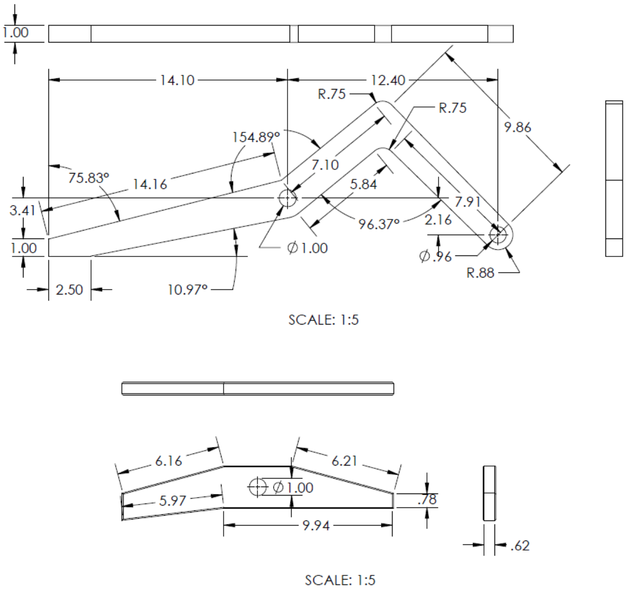


Figure 6: Rocker-Bogie Mechanical Drawing

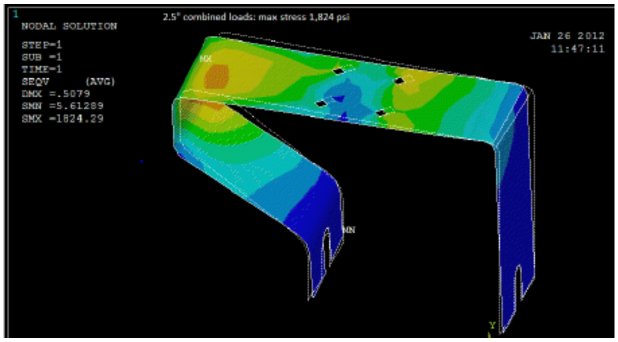


Figure 7: FEA Model of Wheel Mount

The aluminum torque tubes and differential are housed in a Fiberglass Reinforced Plastic (FRP) square channel for rigidity. This channel is installed in an electronics box constructed of lightweight aluminum enclosed by an aluminum cover that creates an external platform. The box is sealed from weather and includes filtered airports for electronics cooling. The interior of the box houses the control and communications system, the power system, and the NAS. The exterior platform houses the cameras, sample acquisition system, antennas for the wireless broadband modem and NAS, emergency stop and battery disconnect switch. The rover peripherals are mounted in and on the electronics box such that the box's center of mass is near the pivot point of the rocker-bogie assembly. These design considerations reflect inspiration from the design of the NASA rovers *Spirit* and *Opportunity* [8].

Propulsion is provided by brushless DC hub motors, commonly used in electric bicycles. They have been modified to allow mounting inside a custom machined PVC wheel and to provide reverse operation. The wheel diameter is 20 centimeters providing ample ground clearance to negotiate 10 centimeter tall obstacles per system requirements. Powerful Torxis i00600 servomechanisms steer the rover, using position-based control. The servomechanisms control the four corner-mounted wheels. This four-wheel steering design allows a near-zero turning radius, allowing the rover to effectively maneuver around obstacles. The rover drive system is displayed in Figure 1.

3.1.2 Sensory System

3.1.2.1 Cameras

An Axis PTZ camera provides the abilities to identify samples of various colors and navigable paths through the mission environment. The Axis camera was chosen because it provides both control and video over a single Ethernet interface. It features an HTTP application programmer's interface (API) providing advanced features such as switchable resolution modes and streaming video.

A second Logitech webcam, fitted with a wide-angle lens, is mounted to the front of the rover and streams video to the WVU Mars Rover UStream site. This provides an obstacle-view camera near ground level and provides video of the rover traversal to allow the public to watch our rover's test live on the Internet.

3.1.2.2 Navigation Assistance System

The navigation method for the rover is teleoperation, based on imagery transmitted from the onboard PTZ camera. Because of communication latency, performing precise movement is difficult – the operator risks 'overshooting' the desired position. The rover employs a NAS, which provides precise inertial data onboard the rover for performing measured movements. The output of the NAS provides gyroscopic input to a control algorithm to properly rotate the robot according to the input of the operator. This allows the operator to issue explicit steering commands (e.g., rotate clockwise 15 degrees) instead of relative commands (e.g., turn clockwise until told otherwise). Similarly, output from the NAS is used to track relative change in position. This allows the operator to issue explicit commands for movement (e.g., move forward 2 meters). Furthermore, the NAS transmits telemetry from the rover including location, velocity, roll, pitch, and heading. It also provides location feedback that is overlaid on a map at the OCU in order to help the operator navigate the mission environment.

Figure 8: Navigation Assistance System

The NAS, shown in Figure 8, uses an Inertial Measurement Unit (IMU), augmented with a Global Positioning System (GPS), to provide traversal information. Data fusion for the two sensor systems is provided by a nine-state Extended Kalman Filter (EKF). The EKF synchronizes the estimates of three-dimensional position (x, y, and z) and velocity (v_x, v_y, and v_z), as well as three attitude axes (roll, pitch, and yaw). The synchronized data provides an estimate of position based on the flat-earth assumption. This estimate is refreshed at a 20 Hz rate and converted to a local coordinate system

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 C^2 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.

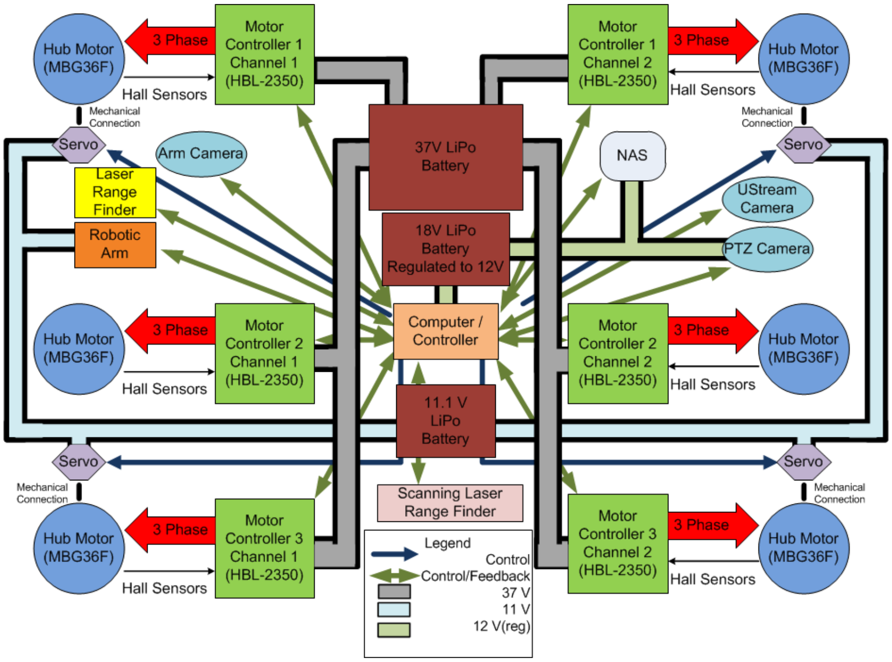


Figure 9: System Diagram

The power system is comprised of the batteries, motor controllers, DC-DC voltage converter, circuit protection, and emergency battery disconnect circuit. Three lithium polymer (LiPo) batteries are required for operation. The 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. A 5 amp-hour (Ah), 37 volt (V) battery was chosen to power the three RoboteQ HBL-2350 motor controllers. A 5 Ah 11V battery powers the steering servos and sample acquisition arm's Dynamixel AX-18 servos. An 8 Ah capacity, 18 V 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 any inducted noise or a large current draw from the motors affecting the control or communications hardware. All battery capacities were selected to provide ample power to complete a 60 minute mission. Figure 9 illustrates the major hardware components, major sensory interfaces, and the individual power legs.

The power system also addresses two major risks. First, LiPo batteries carry a risk of damage if over-discharged. This risk is mitigated through the use of hardware with voltage sensing capability. The RoboteQ motor controllers, Mini-Box DC-DC regulator, and Dynamixel AX-18A Servo controller all offer the ability to shutdown when the battery voltage reaches a programmable minimum, preventing over-discharge [9] [10] [11]. 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

The sample acquisition system comprises a robotic arm with a custom end effector, laser rangefinder, 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 laser rangefinder utilizes a visible laser that can be used to target an object and return the distance to it. A camera, mounted above the wrist section of the robotic arm, returns images corresponding to the attitude and position of the arm to the OCU. 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. The arm end effector, camera and laser rangefinder are shown in Figure 10.

Figure 10: Sample Acquisition Arm End Effector

3.2.1 Arm

The robotic gripper-arm used is a commercial-off-the-shelf (COTS) arm from Crustcrawler Robotics. This arm has a lifting capacity of 0.9 kg and a maximum gripper opening of 14 cm, which exceeds system requirements [12]. It employs eight Robotis Dynamixel AX-18A servomechanisms providing 5 degrees of freedom. Each servo provides position, load, voltage, temperature, and movement status feedback. The servos are position controlled and offer a 300 degree range of motion, with a resolution of 0.29 degrees, and a repeatability of 2.5 mm [13]. This allows for precise positioning of the gripper in order to acquire samples. The forearm section was lengthened to extend the arm's reach and provide a mounting location for the camera and rangefinder. The arm's ability to lift masses in excess of 800 grams was maintained with this modification. The end-effector was modified to operate like an industrial scrap handler, using interleaved *fingers* that can cut through material around the sample and collect the sample in a basket-like structure. The fingers are arranged to hold irregular shaped items of a diameter of 1.5 cm to 9 cm when closed. This end-effector reduces the torque necessary to grasp the sample and maintains better control of the sample throughout the range of motion between the surface and the collection hopper.

3.2.2 Laser Rangefinder

A Fluke 411d Laser rangefinder, controlled by a Porcupine Electronics USB interface board is mounted on the arm, above the first joint. The rangefinder provides a targeting sight that can be placed on an object of interest within 30 m of the rover [14]. The rangefinder returns the distance of the object which, combined with the position and attitude of the rover and arm, can be used to determine a path to the object using inverse kinematics. As the rover closes in on the object, the rangefinder tracks the distance between the end-effector and the target. The feedback of the rangefinder is used to stop the rover when it has achieved a position near the target.

3.2.3 Camera

A small color camera endoscope with wide-angle lens is attached to the forearm section of the arm and aimed at the end-effector. This provides the operator with a view of the object to be acquired, allowing for better control of the arm. The camera is aimed in the same direction as the laser rangefinder allowing quick target acquisition of samples

3.2.4 Collection Bin

A collection bin is incorporated on the front of the rover for storing retrieved samples. The collection bin is constructed of high-strength nylon mesh on a lightweight aluminum frame to allow expansion and suspension of the samples while allowing smaller particles to escape so that valuable volume is not wasted. The volume, before expansion, of the collection bin is 10,000 cubic centimeters. This design allows ample room to collect 30 samples of an 8 cm diameter.

3.2.5 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, such as depositing samples in the collection bin. 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) [15] . These coordinates allow the software to store and move to preset positions autonomously.

3.3 Control and Communication Systems

The C^2 subsystem includes the hardware and software necessary to control and communicate with the drive and sample acquisition systems. The C^2 sub system includes the Robot Control Unit (RCU), motor controllers, arm servo controller, Operator Control Unit (OCU), wireless broadband modem, and WVU network.

The rover is controlled by two computers: the OCU and RCU. The OCU is housed on a server at WVU. It displays video and telemetry from the rover and serializes operator input to be transmitted to the rover. The RCU resides on the rover and provides four primary functions: receiving and parsing control state data from the OCU, executing algorithms for autonomous operation macros, interfacing to the attached devices and controllers, and relaying video and telemetry to the OCU. The two control units are linked by a communications system incorporating a wireless broadband modem. Figure 11 shows the communications relationship between the OCU and RCU.

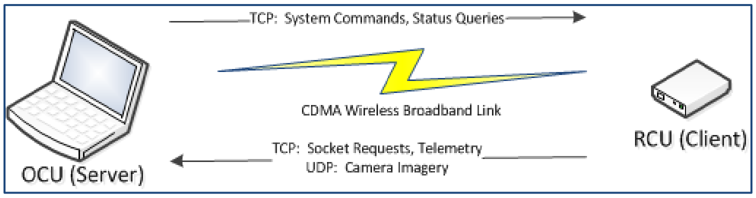


Figure 11: Communications Diagram for OCU/RCU

3.3.1 Control Hardware

3.3.1.1 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 1.86 GHz Intel Atom N2800 low-power-consumption processor. The N2800 has a low thermal design power (TDP) of 8W and also provides significant computing capability with a 1.86 GHz clock speed [16]. The processor is mounted in a passively cooled industrial-grade Intel DN2800MT Marshalltown Mini-ITX motherboard. The board supports 2 RS-232 ports on integrated headers [17] and 4 more through the use of a Jetway 4-port RS-232 Mini-PCIe module. While the motor controllers, arm controller and NAS support both serial and USB connections, RS-232 has better recovery in the presence of electrical issues [9]. 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 [18].

3.3.1.2 Motor Controllers

Three RoboteQ HBL-2350 2-channel brushless DC motor controllers were chosen to control the rover's six motors. These advanced motor controllers provide open- or closed-loop motor control utilizing the Hall-effect sensors in each wheel [19]. Each wheel is individually powered allowing a level of redundancy; if 1 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 [20], yet it was able to continue its mission for over 3 years after the failure [21].

3.3.1.3 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.

3.3.2 Control and Communications Software

The communications system is crucial for proper teleoperation of the rover from the remote site on WVU's campus. The requirements dictate that the rover utilize a Verizon wireless modem, however Verizon Wireless does not offer 3G or 4G wireless service in the vicinity of WVU. For this reason, 3G wireless testing is being performed with a US Cellular PCD UM185 3G wireless modem.

The US Cellular wireless modem operates behind a double network address translation (NAT) layer exactly as their Verizon wireless phone counterparts, thus it is expected that the Verizon wireless modem will exhibit similar behavior. The behavior of the double NAT layer on the 3G wireless requires that the communications software on the RCU be a TCP/IP Client. A TCP/IP client has the ability to "punch through" the double-NAT layer and establish a connection to the OCU server software at WVU.

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.

3.3.3 Network Communication Software

The wireless modem based network 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, the packet 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 movement 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.

3.3.4 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 from the communications system. The OCU and RCU maintain a heartbeat signal between them 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 and Axis camera imagery is 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 [22]. 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.

3.3.5 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 12.

The sample acquisition operator can operate the robotic arm and laser rangefinder, 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 13. Any changes are then forwarded to the RCU and immediately enacted. This allows the operators to improve image quality when fine 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.

Figure 12: Example of rover tracking using Google Earth

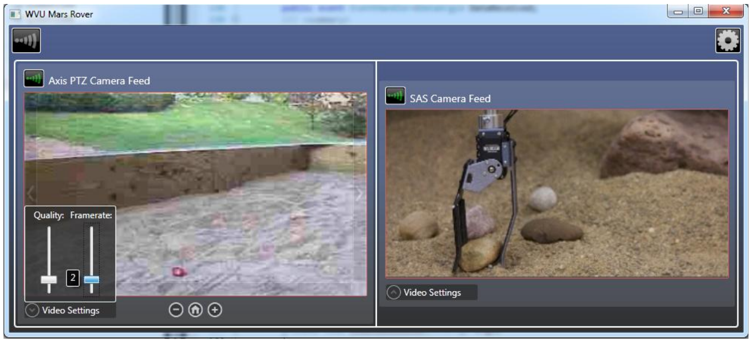


Figure 13: OCU software demonstrating dynamic adjustment of video parameters

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 3G 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 in addition to a 54% obstacle strewn grade. Tests were carried out with the operators quarantined in the server room, operating using rover video. The NAS has been independently tested and has demonstrated heading accuracy within 2 degrees and acceptable GPS accuracy. Figure 14 shows the robot in the sandbox test environment.

Figure 14: Mars Rover in Validation Area

The robot is currently undergoing an extensive verification review against the requirements definition as well as end-to-end validation tests prior to the Checkout/Final Validation Review May 16, 2012.

5 Education and Public Outreach

Education and public outreach is an important component part of the NASA-NIA RASC-AL Exploration Robo-Ops Competition. The WVU Mountaineers rover team combined forces with the WVU Lunabotics team, the Society of Women Engineers (SWE), the NASA West Virginia Space Grant Consortium (WVSGC), and the NASA Independent Validation and Verification (IV&V) center to provide a large amount of quality public outreach informing students about opportunities in STEM fields and encouraging them to pursue studies in the STEM disciplines.

Projects were divided into presentation and interactive activities. In order to increase effectiveness with the interactive activities, the Mountaineers received over 100 hours of certified formal training from the NASA IV&V Educator Resource Center (ERC). Select members were trained in teacher workshops and the effective use of rocketry and Lego® Mindstorm educational kits. The team traveled to regional schools, supplementing teachers' curriculums with the provided educational kits. The Mountaineers also planned a variety of workshops of their own, designed for different age groups, utilizing robotics to encapsulate some of the most exciting aspects of STEM.

Having a large team allowed the Mountaineers to perform a vast amount of outreach projects. The Mountaineers tracked their outreach events and kept these metrics in the Outreach Log, located in Appendix E. The Mountaineers dedicated 100 hours of training and 201 quality hours outreach activities. They interacted with approximately 2,500 different students, promoting the Science, Technology, Engineering and Mathematics (STEM) initiative. The primary activities presented by the Mountaineers follow below, organized into *Presentation Activities* detailed in Section 5.1 and *Interactive Activities* detailed in Section 5.2.

5.1 Presentation Activities

5.1.1 "Careers in the Corridor" and "A Day in the Park"

NASA IV&V Educational Outreach hosts both the "Careers in the Corridor" and "A Day in the Park" events in collaboration with the West Virginia High Technology Consortium Foundation. These events are located at the Technology Park Research Center at the NASA IV&V Facility in Fairmont, WV.

The first event, “Careers in the Corridor”, is organized for exceptional tenth-grade students from several Morgantown, WV area high schools. The purpose of the event is to show students different career options available to them if they pursue STEM fields. The team presented an informative slideshow and robotics demonstration detailing the teamwork and design aspects involved in the competition to an auditorium full of captivated high school students. The presentation focused upon the STEM aspects utilized in this real-world project and encouraged students to pursue their interests in a STEM career field.

The second event, “A Day in The Park”, is a two-day outreach attended by over 300 seventh grade students from North Central West Virginia. The goal of this event, as stated by the Event Coordinator, is “to raise awareness and get kids excited about STEM.” The Mountaineers set up an exhibit in which they demonstrated their 2011 Lunabot. The Mountaineers explained the capabilities of the robot, how the different components were made, and how the robot met its stated mission. Figure 15 shows a demonstration and answer session. This 4-hour event offered the team ample time to get to know the students they talked to and tell them about the importance of doing well in their math and science classes so that one day they could be a part of a similar project.

Figure 15: Discussing Robotics

5.1.2 High School Visitation Day

The Mountaineers were invited to attend “High School Visitation Day” hosted by West Virginia University. This event is for high school students who are considering attending WVU. This event provided the team the opportunity to interact with a large variety of students. It was attended by approximately 350 students and parents from schools located all over the country. The team’s focus in the event was to utilize their robotics projects to inform students of the opportunities available in the areas of STEM. The Mountaineers presented their experiences and opportunities made available to them by NASA and WVU. The event ended with many questions from the audience, indicating a high level of engagement.

5.1.3 Eighth-Grade Career Day of Monongalia County

The annual “Eighth-Grade Career Day of Monongalia County”, held every spring, encourages eighth-grade students to start considering their career path as they prepare to graduate to High School. Almost 800 students from Monongalia County attended the event. Professionals from a variety of North-Central WV businesses prepare educational activities and instructional materials for students of Monongalia and surrounding counties. The Mountaineers were invited to participate in this event to support the WVSGC. The team demonstrated a variety of robots to show students how the STEM fields can be employed in real-world applications. Students were engaged, asking how robots are built, how long fabrication takes, and what steps they needed to take as they progressed through their education to participate in robotic development projects. Figure 16 shows a team member demonstrating the rover for the students.

Figure 16: Presenting Mars Rover

5.2 Interactive Activities

5.2.1 Lego Mindstorms Robotics Lesson

The Mountaineers coordinated with the principal of Cheat Lake Elementary, Dennis Gallon, to supplement his teachers' curriculum with the Lego Mindstorms NXT Workshop. The Mindstorms NXT kits allow students to easily fabricate and program simple robots, providing the students with a hands-on application of STEM knowledge. The Mountaineers received the opportunity to spend 2 hours teaching 30 fifth-grade students about robotics using these kits.

Students teamed up in small groups to complete the activities. Each group of students constructed a robot then learned how to communicate with it using the NXT 2.0 software. Figure 17 shows students programming with the software. Once communications were established, students created programs controlling the robots' basic behavior, implementing simple actions such as *move forward* or *move backward*. Finally, students were given instructions to program the robots to move forward across the table, as close to the edge as possible without falling off, turn the robot 360 degrees around, and even navigate an obstacle course. In each situation, students were provided with the tools and relationships necessary to complete the activity. By the end of the workshop, every team had successfully completed all the activities. During the final portion of the workshop, students discussed programs which may be encountered in everyday life.

Figure 17: Programming NXT software

5.2.2 Bluefield Workshop

The Mountaineers partnered with their sponsor, the NASA WVSGC in a workshop hosted by the Emerging Leaders Institute (ELI) at Bluefield State College. The ELI was established to foster academic excellence in African American Students by providing them with the opportunity to pursue a quality education. This workshop was given to 45 high school seniors who come from an underprivileged area in Bluefield. The Mountaineers presentation focused on the benefits of a college degree in STEM fields.

5.2.3 Girl Scouts "Discovering Technology" Badge

The Mountaineers coordinated with WVU's SWE chapter to help Girl Scouts from the North-Central WV region, ranging in age from 9-12 years old, achieve their Discovering Technology Badge. This event was a great way to present the benefits of the STEM fields to young girls supporting one of SWE's primary missions of encouraging women to pursue careers in engineering.

In order for the Girl Scouts to receive the "Discovering Technology" badge, they had to complete several tasks, which the volunteers from the WVU Mountaineer rover team guided and advised them through. The scouts were divided into groups, each of which was guided through the activities by two team members. In the first activity Scouts discussed examples of items incorporating microchips, such as iPods, cell phones, and cameras. Then each group compiled a list of at least twenty-five objects which make use of computers, and what purpose they served. The second activity required each scout to identify a career they would consider when they grow up. These careers were compiled into lists and the scouts were asked to identify how technology affected the fields. Finally, several different student-built autonomous and teleoperated robots were demonstrated to the scouts to provide examples of applied technology. The Girl Scouts visited each robot demonstration in stations, learning about what the robot did and how it functioned; this can be seen in Figure 18. They then interacted with the robots under the supervision of the team members, and many remarked that the robots were their favorite part of the day.

Figure 18: Girl Scouts Visiting Robotic Stations

5.2.4 Eighth Grade Engineering Career Day

The purpose of this event, organized by the WVU's SWE chapter, was to introduce eighth-grade students to careers in the fields of science and technology. Attendees included over 120 students and twelve chaperones from 6 different schools in West Virginia. The students were broken into 4 groups of about 30 students. Each group visited each of 8 stations as well as an opening and closing presentation.

At the Mountaineers' station the students received a presentation on

Figure 19: Team members presenting robot demonstration

robotics, shown in Figure 19, and were introduced to the rocketry workshop. This workshop teaches the students the basic science and physics needed to optimize the flight characteristics of a rocket and offers students a hands-on opportunity to build a rocket out of straws, paper, tape, and clay. The students were then taken outside to launch their rockets. After the launch, the Mountaineers asked the students to quantitatively analyze the performance of the rockets by measuring the distance traveled. Team members then helped the students assess the rockets' performance by analyzing the distance traveled and flight pattern. The students concluded that heavier rockets, rockets with larger tail fins, and rockets without a forward center of gravity (measured by balancing the rocket on the student's finger) did not go as far as lighter rockets with smaller tail fins (less drag) and a slightly forward center of gravity. These conclusions indicated that the students were able to understand advanced science and physics concepts such as center of gravity, trajectory, aerodynamics, and drag through the use of this accredited workshop.

5.2.5 First Lego League (FLL) Robotics Tournament

The WV First Lego League is a NASA Classroom of the Future program directed by Meri Cummings and sponsored by WVSGC. This year's FLL State tournament was held at Ripley High School and attended by 39 teams, totaling more than 350 students, ranging in age from 9-14 years old from all over the state of West Virginia. The First Lego League is a competition promoting STEM through robotics projects. The Mountaineers were offered this outreach opportunity by WVSGC due to their training and experience with Mindstorms Robots.

The preparation for this event offered the Mountaineers to apply their technical skills to support activities such as setting-up the sound system and projectors, soldering connections for the overhead cameras, running electrical wiring, and networking the computers for the competition. During the competition the Mountaineers participated in the event setting tables, managing staging, and refereeing the competition, as shown in Figure 20.

Figure 20: Refereeing FLL Competition

6 Conclusions

The WVU Mountaineers Rover Team set forth in early 2012 to design a planetary rover, capable of exploring a foreign surface, collect samples and be controlled from hundreds of miles away for the objective of winning the 2012 RASC-AL Exploration Robo-Ops Competition. The team applied fundamental systems engineering processes to develop a quality product in an accelerated, nineteen-week schedule. These processes allowed concurrent work among specialized teams to maximize productivity. The rover was developed utilizing the incremental life-cycle systems development model, and through several iterations, product improvement has been realized. Verification practices were employed throughout the design process to ensure that the end product would meet requirements. Validation of the rover was carried out at the end of each lifecycle iteration in test environments that reflect the requirements of the competition including a steep rocky hill and sandbox filled with large rock obstacles to evaluate the degree to which the system capabilities met the objectives and requirements for the system. This process allowed the team to identify deficiencies and opportunities to optimize their design, thus building a better product through iteration.

The Mountaineers found the Outreach portion of the RASC-AL competition very rewarding. The team reached approximately 2,500 students in a total of 15 outreach events, sharing their passion for STEM education. The team's outreach efforts will continue through the competition by encouraging the public to watch our test on the streaming website. The Mountaineers were proud to share the NASA mission of public outreach and education during this project.

This project has provided an excellent hands-on opportunity for the team members to apply their classroom knowledge and creativity to develop a complex system capable of completing a challenging mission. Furthermore it has provided an opportunity to share the STEM fields with the public through outreach efforts. The team looks forward to competing in the 2012 RASC-AL Exploration Robo-Ops Competition.

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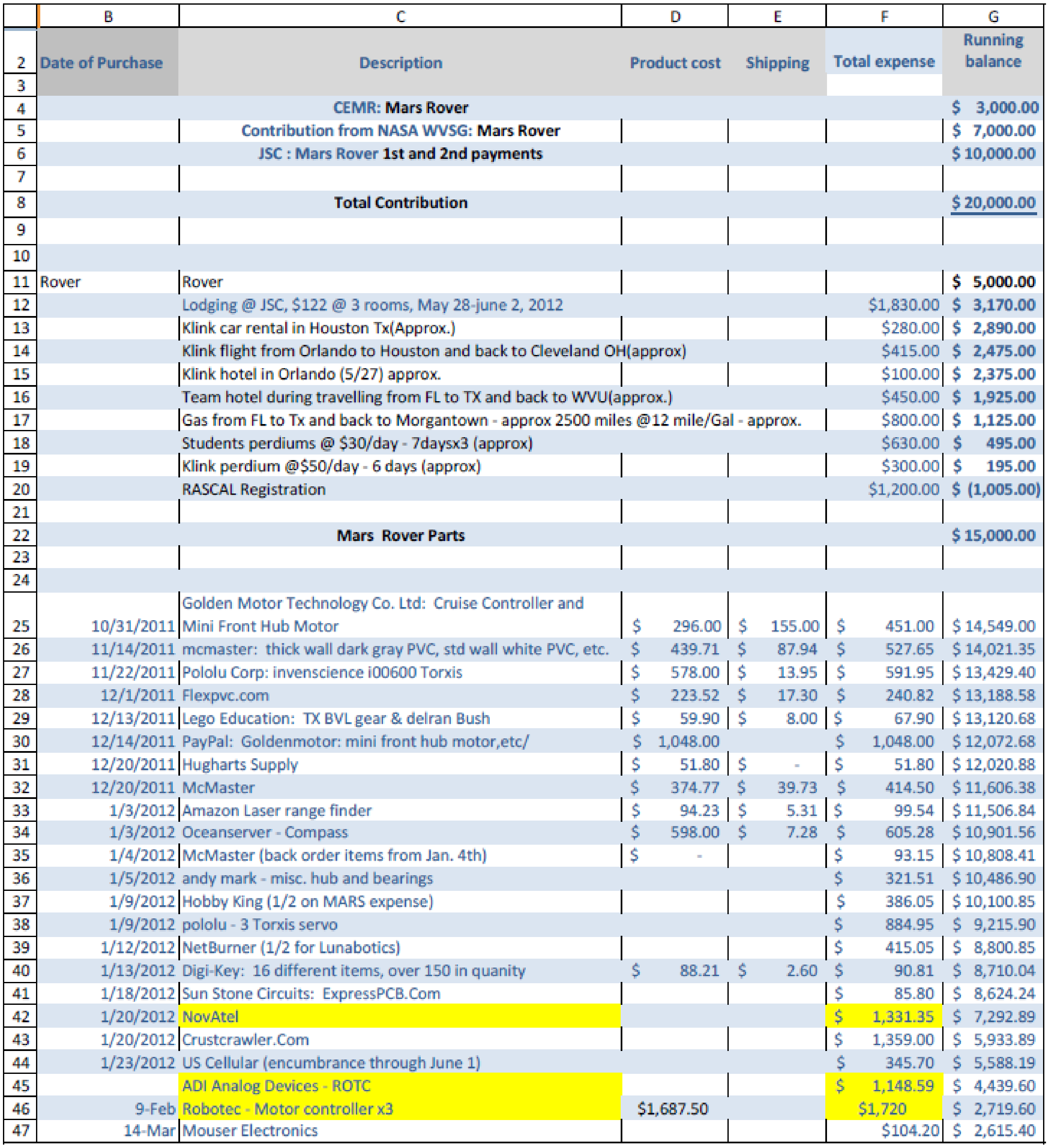
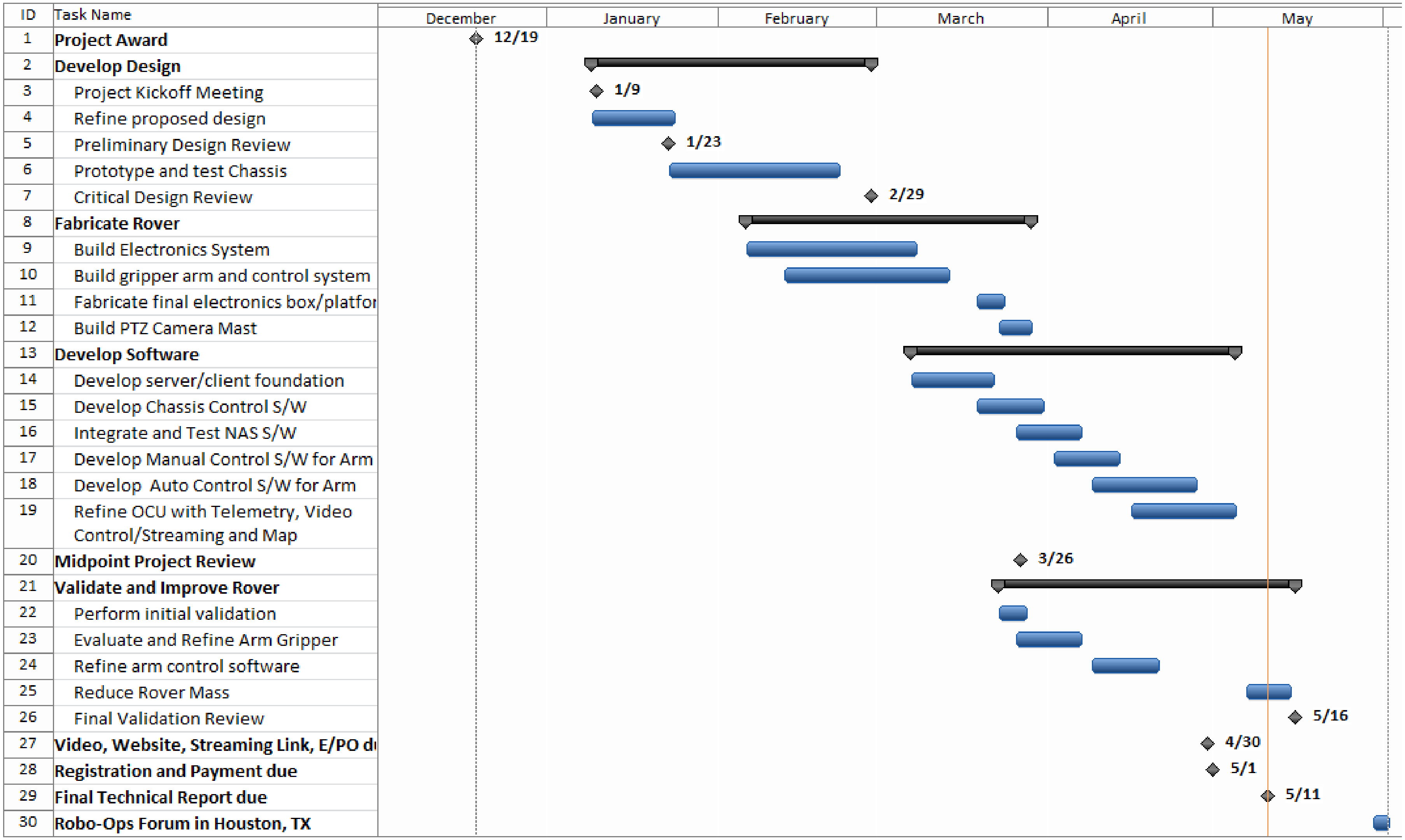
Appendix A: Budget Balance Sheet



	B	C	D	E	F	G
2	Date of Purchase	Description	Product cost	Shipping	Total expense	Running balance
3						
4		CEMR: Mars Rover				$ 3,000.00
5		Contribution from NASA WVSG: Mars Rover				$ 7,000.00
6		JSC : Mars Rover 1st and 2nd payments				$ 10,000.00
7						
8		Total Contribution				$ 20,000.00
9						
10						
11	Rover	Rover				$ 5,000.00
12		Lodging @ JSC, $122 @ 3 rooms, May 28-june 2, 2012			$1,830.00	$ 3,170.00
13		Klink car rental in Houston Tx(Approx.)			$280.00	$ 2,890.00
14		Klink flight from Orlando to Houston and back to Cleveland OH(approx)			$415.00	$ 2,475.00
15		Klink hotel in Orlando (5/27) approx.			$100.00	$ 2,375.00
16		Team hotel during travelling from FL to TX and back to WVU(approx.)			$450.00	$ 1,925.00
17		Gas from FL to Tx and back to Morgantown - approx 2500 miles @12 mile/Gal - approx.			$800.00	$ 1,125.00
18		Students perdiums @ $30/day - 7daysx3 (approx)			$630.00	$ 495.00
19		Klink perdium @$50/day - 6 days (approx)			$300.00	$ 195.00
20		RASCAL Registration			$1,200.00	$ (1,005.00)
21						
22		Mars Rover Parts				$ 15,000.00
23						
24						
25	10/31/2011	Golden Motor Technology Co. Ltd: Cruise Controller and Mini Front Hub Motor	$ 296.00	$ 155.00	$ 451.00	$ 14,549.00
26	11/14/2011	mcmaster: thick wall dark gray PVC, std wall white PVC, etc.	$ 439.71	$ 87.94	$ 527.65	$ 14,021.35
27	11/22/2011	Pololu Corp: invenscience i00600 Torxis	$ 578.00	$ 13.95	$ 591.95	$ 13,429.40
28	12/1/2011	Flexpvc.com	$ 223.52	$ 17.30	$ 240.82	$ 13,188.58
29	12/13/2011	Lego Education: TX BVL gear & delran Bush	$ 59.90	$ 8.00	$ 67.90	$ 13,120.68
30	12/14/2011	PayPal: Goldenmotor: mini front hub motor,etc/	$ 1,048.00		$ 1,048.00	$ 12,072.68
31	12/20/2011	Hugharts Supply	$ 51.80	$ -	$ 51.80	$ 12,020.88
32	12/20/2011	McMaster	$ 374.77	$ 39.73	$ 414.50	$ 11,606.38
33	1/3/2012	Amazon Laser range finder	$ 94.23	$ 5.31	$ 99.54	$ 11,506.84
34	1/3/2012	Oceanserver - Compass	$ 598.00	$ 7.28	$ 605.28	$ 10,901.56
35	1/4/2012	McMaster (back order items from Jan. 4th)	$ -		$ 93.15	$ 10,808.41
36	1/5/2012	andy mark - misc. hub and bearings			$ 321.51	$ 10,486.90
37	1/9/2012	Hobby King (1/2 on MARS expense)			$ 386.05	$ 10,100.85
38	1/9/2012	pololu - 3 Torxis servo			$ 884.95	$ 9,215.90
39	1/12/2012	NetBurner (1/2 for Lunabotics)			$ 415.05	$ 8,800.85
40	1/13/2012	Digi-Key: 16 different items, over 150 in quanity	$ 88.21	$ 2.60	$ 90.81	$ 8,710.04
41	1/18/2012	Sun Stone Circuits: ExpressPCB.Com			$ 85.80	$ 8,624.24
42	1/20/2012	NovAtel			$ 1,331.35	$ 7,292.89
43	1/20/2012	Crustcrawler.Com			$ 1,359.00	$ 5,933.89
44	1/23/2012	US Cellular (encumbrance through June 1)			$ 345.70	$ 5,588.19
45		ADI Analog Devices - ROTC			$ 1,148.59	$ 4,439.60
46	9-Feb	Robotec - Motor controller x3	$1,687.50		$1,720	$ 2,719.60
47	14-Mar	Mouser Electronics			$104.20	$ 2,615.40

Appendix B: Project Schedule Gantt Chart



ID	Task Name
1	**Project Award**
2	**Develop Design**
3	Project Kickoff Meeting
4	Refine proposed design
5	Preliminary Design Review
6	Prototype and test Chassis
7	Critical Design Review
8	**Fabricate Rover**
9	Build Electronics System
10	Build gripper arm and control system
11	Fabricate final electronics box/platfor
12	Build PTZ Camera Mast
13	**Develop Software**
14	Develop server/client foundation
15	Develop Chassis Control S/W
16	Integrate and Test NAS S/W
17	Develop Manual Control S/W for Arm
18	Develop Auto Control S/W for Arm
19	Refine OCU with Telemetry, Video Control/Streaming and Map
20	**Midpoint Project Review**
21	**Validate and Improve Rover**
22	Perform initial validation
23	Evaluate and Refine Arm Gripper
24	Refine arm control software
25	Reduce Rover Mass
26	Final Validation Review
27	**Video, Website, Streaming Link, E/PO d**
28	**Registration and Payment due**
29	**Final Technical Report due**
30	**Robo-Ops Forum in Houston, TX**

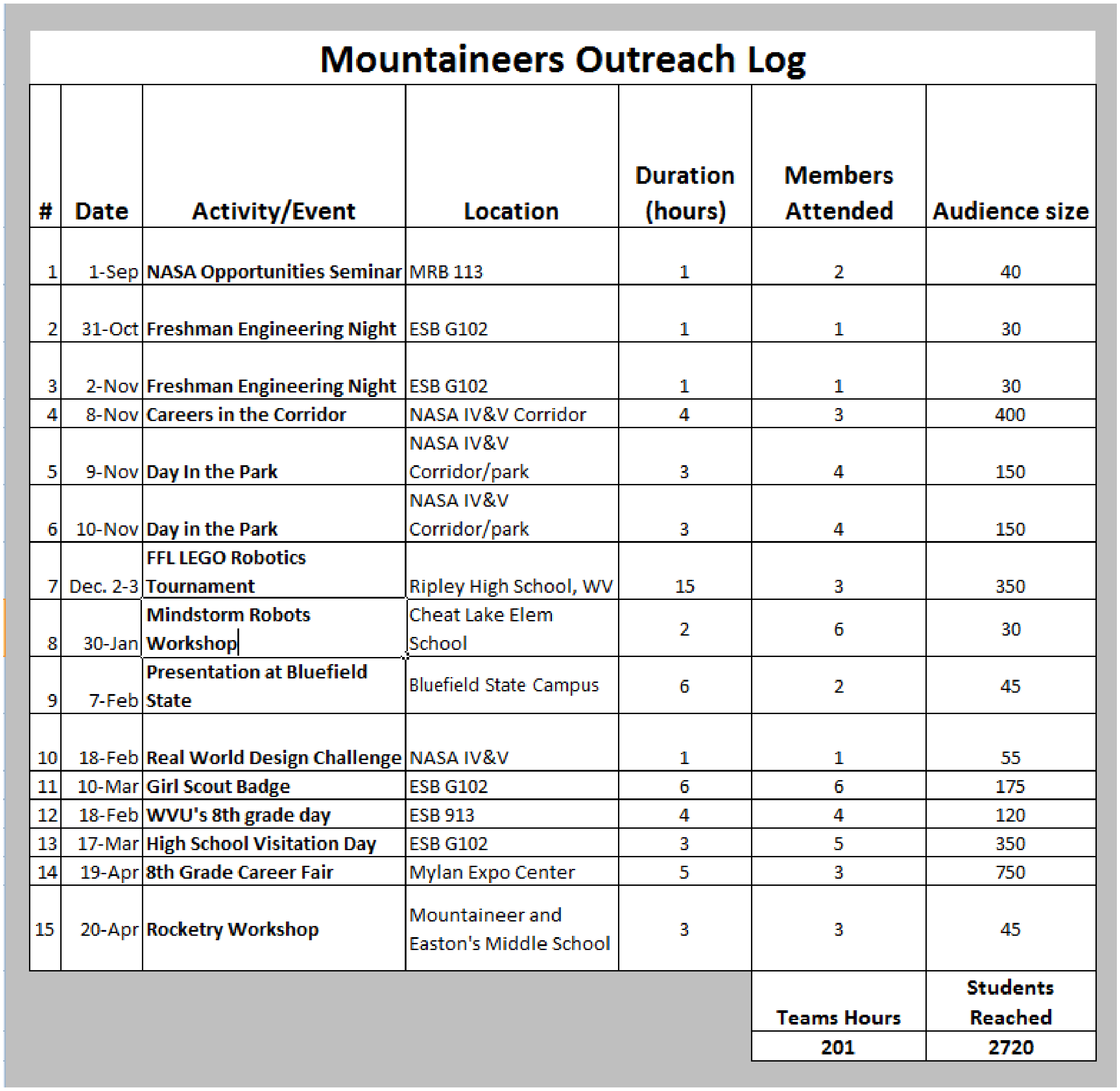
Appendix C: System Requirements Document

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 D: Risk Management Matrix

Risk	Category	Effect	Mitigation
Lithium Polymer 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 three 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.
Hokuyo rangefinder(s) failure	Low	If the rangefinder is obscured or stops operating the robot will lose the ability to detect near obstacles.	Use only camera to navigate and operate with additional caution.
Arm rangefinder failure	Low	If the rangefinder fails the ability to target rocks is lost.	Use only camera to acquire samples
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

Appendix E: Outreach Logbook



Mountaineers Outreach Log

#	Date	Activity/Event	Location	Duration (hours)	Members Attended	Audience size
1	1-Sep	**NASA Opportunities Seminar**	MRB 113	1	2	40
2	31-Oct	**Freshman Engineering Night**	ESB G102	1	1	30
3	2-Nov	**Freshman Engineering Night**	ESB G102	1	1	30
4	8-Nov	**Careers in the Corridor**	NASA IV&V Corridor	4	3	400
5	9-Nov	**Day In the Park**	NASA IV&V Corridor/park	3	4	150
6	10-Nov	**Day in the Park**	NASA IV&V Corridor/park	3	4	150
7	Dec. 2-3	**FFL LEGO Robotics Tournament**	Ripley High School, WV	15	3	350
8	30-Jan	**Mindstorm Robots Workshop**	Cheat Lake Elem School	2	6	30
9	7-Feb	**Presentation at Bluefield State**	Bluefield State Campus	6	2	45
10	18-Feb	**Real World Design Challenge**	NASA IV&V	1	1	55
11	10-Mar	**Girl Scout Badge**	ESB G102	6	6	175
12	18-Feb	**WVU's 8th grade day**	ESB 913	4	4	120
13	17-Mar	**High School Visitation Day**	ESB G102	3	5	350
14	19-Apr	**8th Grade Career Fair**	Mylan Expo Center	5	3	750
15	20-Apr	**Rocketry Workshop**	Mountaineer and Easton's Middle School	3	3	45
					Teams Hours	**Students Reached**
					201	**2720**