



Team PYREX



2014 Robo-Ops Final Technical Report

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Chapter 1: Background and Motivation

Virginia Tech will be entering Animus, the nickname of the team's rover, into the 2014 RASC-AL Exploration Robo-Ops Competition. Built and developed by eight undergraduate students under the guidance of the Aerospace Department, Animus is designed to function as a tele-operated rover in a planetary simulated environment. Animus's systems were designed with a primary focus to swiftly and effectively traverse the varying terrain of the course. As the University's first entry into the competition, PYREX (Planetary Rover EXploration) hopes to prove Animus's capabilities in completing the objectives outlined in the competition's guidelines as well as establish the groundwork for future teams to compete. Along with developing this rover, PYREX has actively networked with companies to sponsor Virginia Tech in Animus's development as well as working with the local community in public outreach programs to promote further interest in the project.

Chapter 2: Description of System Components

Animus features a rocker-bogie suspension system with four wheeled steering and six wheeled drive. Although challenging to manufacture, this design has proven to have benefits that outweigh the time investment needed to form such a complex structure. The rocker-bogie suspension and drivetrain components increase the chance for the rover to have all six wheels in contact with a terrain at a given moment, ensuring minimal wheel slip.

Having a rover capable of navigating complex terrain is complimented by a user-friendly control system. Onboard Animus are two Verizon hotspots that provide a 4G internet connection to an onboard computer. A UDP connection then allows the operator in Blacksburg to control three cameras, all rover drive functionality, a five degree of freedom (DOF) manipulating arm, and access to various sensors.

When selecting these components, it was necessary to ensure the correct decision was made to achieve our goals. Initially, an analytical hierarchy process (AHP) was used to numerically rank criteria based on different alternatives to attain an unbiased result. However, in a complex group environment pressured by time, a rapid prototyping approach was adapted. This method utilized computer aided design (CAD) and preliminary calculations, followed by initial prototyping, and then iterative refinement until a final product was realized. With the support of subdivision and team leaders, this process proved to be very efficient while still being reinforced by numerical data. The products of PYREX's decisions are detailed below:

Description of Chassis and Suspension Mechanisms. The rover's chassis takes the form of a simple rectangular shape. A rectangular frame maximizes platform area for mounting components and it is simple to manufacture. The final chassis can be seen in Figure 1. It is mainly comprised of 6061 Aluminum $\frac{3}{4}$ inch square tubing and G10-FR4 fiberglass brackets. Using these two materials allowed the team to quickly fabricate and test different configurations to find optimal dimensions and fastening techniques.

The chassis in Figure 1 weighs 2.0 kg and provides the blank platform to build the rover around. The frame is 0.838 meters long, 0.457 meters wide, and .114 meters high. These

dimensions give the rover room for mounting components and remain within the maximum size limits. The frame is held together by brackets and screws allowing parts to be interchanged.

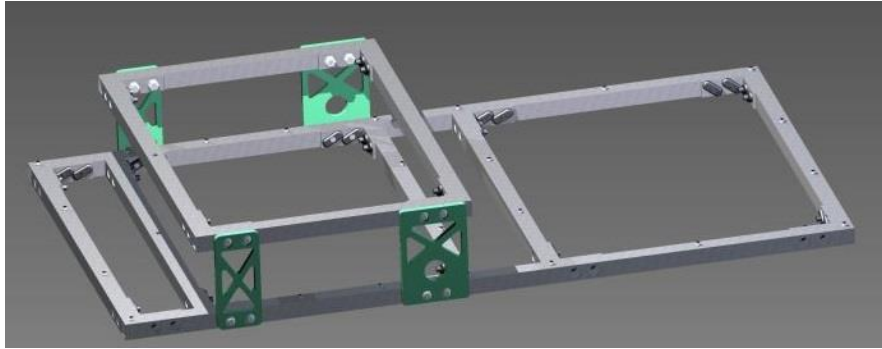


Figure 1 – Final Rover Frame. A detailed CAD of the blank rover chassis. This provided the rover with a large area that could easily be fitted with all the necessary systems and components.

The rover utilizes a six wheeled rocker-bogie system. The rocker-bogie configuration can be seen in Figure 2. The advantages to using this system are that the rover is able to maintain contact between all of its wheels and the ground while maneuvering over obstacles. Distributing the weight and drive torque to six wheels instead of four, gives the rover greater traction and stability.

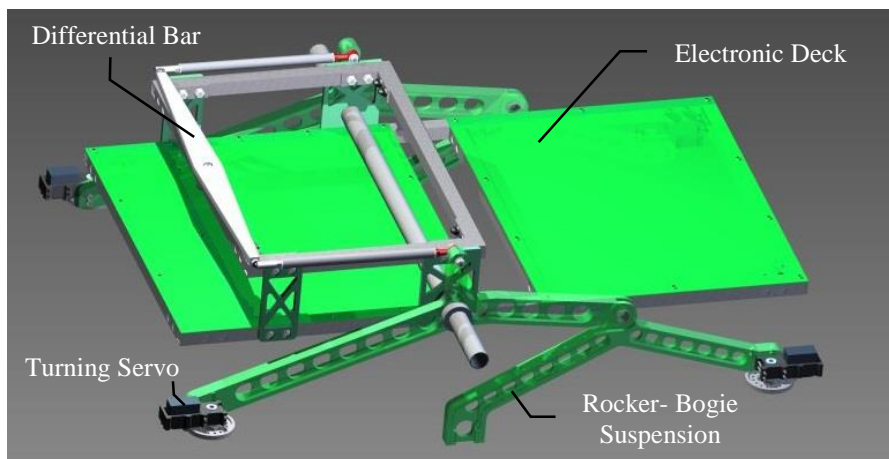


Figure 2 - Completed CAD model of rover chassis and suspension system. There are 2.38 mm thick FR4-G10 fiberglass sheets mounted on the deck of the rover's frame, to allow for easy mounting. The differential bar is located on the top of the assembly, and turning motors are seen at the ends of the suspension system.

The rocker-bogie legs are comprised of $\frac{3}{4}$ inch thick G10-FR4 fiberglass. Figure 3 highlights the fabrication process of rocker-bogie legs. This material has a lower density than aluminum, and as such a lower yield strength.



(3.1)



(3.2)



(3.3)

Figure 3 – Construction of Suspension Pieces. Above highlights some of the work involved in perfecting a suspension arm. Four individual pieces were crafted for use on the rover, plus a spare bogie arm.

After assembling the rocker-bogie suspension to the frame, some degree of torsional bending was bowing the wheels outwards. This bowing is known as camber gain, and is caused by the flexibility in the fiberglass arms and from a large kingpin offset between the longitudinal centers of the wheel and the suspension. To counter camber gain, a slight toe-in adjustment was given to the front steering wheels and a front sway bar was added to the rover. Rigidity through the suspension system was achieved by the use of a differential bar. The solid $\frac{1}{4}$ inch thick 6061 Aluminum differential bar can also be seen in Figure 2 above. To minimize the stress on this bar, ridged body dynamics were used to investigate areas throughout the suspension system that could be modified.

The triangle shown in Figure 4 is created from the main axel, differential bar, and the top of the suspension system. This triangle plays a very important part on the overall rigidity of the system. If all other dimensions are kept the same, varying the height, H , in Figure 4 also varies the angle θ . As the value of θ increases and becomes close to 90° , the forces required to keep the rover system rigid become exponentially increased. The optimal angle of θ would be 45° , as this would evenly distribute the forces between all components in the suspension system. Due to the rover's height restriction limits, an angle of 45° was not possible. The maximum angle θ that was obtained while staying below the height restrictions was 69° .

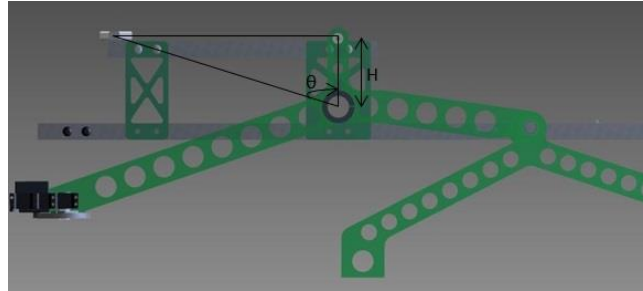


Figure 4 – Side view of rocker bogie suspension system. The distance H is the relationship between the height of the main axel and the height of the differential bar. This distance plays a key role in determining the overall rigidity of the rover system.

Design of Wheels for Optimal Traction. It was necessary to research vehicle dynamics and terramechanics theories to derive a proper wheel for Animus. Thankfully, Virginia Tech offers a class on land vehicle dynamics, and has professors such as Dr. Saied Taheri and Dr. Mehdi Ahmadian (both leaders in vehicle and tire systems) available for support. The equations and branching theories behind wheel terramechanics are quite indepth, and will not be covered in the scope of this report. For more information, see reference ^[1]. Instead, this section gives a brief overview of the basic physics involved in wheel design and terramechanics.

Terramechanics, or the interaction between a soil and a tire can be modeled as a rigid case or an elastic case. For the purpose of this design, a rigid wheel case was used. This assumes no tire deflection, and no pneumatic inflation pressure within the tire. A rigid wheel will sink into a soil to some degree, have a certain slip velocity, deform the soil to some amount, and have a resistive self-aligning force in the lateral and longitudinal wheel direction. This is largely based on the contact patch the wheel makes with the soil, and the load on each individual wheel. The contact patch dimension is a function of wheel radius and width, so it was necessary to select a size that met desired weight constraints, vehicle speed, and various other limiting size factors.

A MatLab program was developed that allowed a user to change tire dimensions, loading force, and terrain properties (ranging from firm to soft soil) in order to optimize a wheel design. The parameters used for the soil properties can be found in reference ^[1]. Below is a Figure that depicts the sinkage of a wheel based on the contact angle.

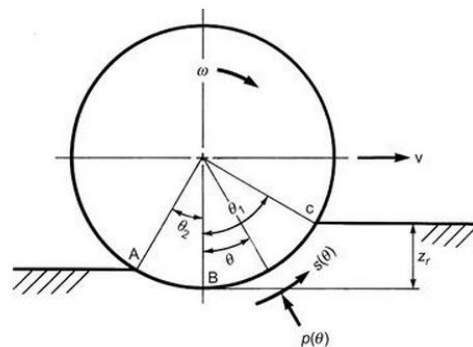


Figure 5 - Representation of interaction between a rigid wheel and soil interface. It should be noted in this figure that the velocity V is to the right, angular velocity w is clockwise, Z_r is the wheel sinkage, and the wheel is in contact with the soil from points C to A ^[1]. $P(\theta)$ is the pressure distribution and $S(\theta)$ is the shear displacement distribution.

After iteratively running the Matlab program under different inputs, it was found that an 20.32 cm diameter wheel at 12.7 cm wide would prove to have the most tractive benefits under all soils. Knowing the degree of wheel sinkage for this case and assuming a slip percentage of 3% (used as a standard amount of wheel slip [2]), another Matlab program was made to derive the needed lug height and thickness. There is a relationship between the tread spacing and lug height, which was found to meet our needs at a spacing of 16.68° . To simplify this model, Animus uses twenty-two repeating tread patterns at a lug height of 8.89 mm and a sidewall thickness of 3.81 mm. A simple curved tread pattern was used to clear debris easily while providing enough resistance to travel through sand.

Further calculations used the known wheel properties to derive the required torque for steering and driving up a hill of 33 percent grade, through sand, and at a desired operation velocity of 1.5 meters per second. It was found that the motors would need a total drive torque of 10.2 N.m at 143.3 RPM, and the steering motors would need a total of torque of 4.8 N.m. The use of six wheels also shows benefits here by splitting the needed torque for each motor six ways instead of four.

Knowing the desired wheel properties, construction could begin. A G10-FR4 fiberglass wheel hub was used to provide rigidity and remove unecessary weight caused by metal. A similar 8 in. fiberglass wheel shell was used which would later have tread applied on the outer surface. Figure 6 below shows the final wheel design after performing a finite element analysis and initial prototyping.

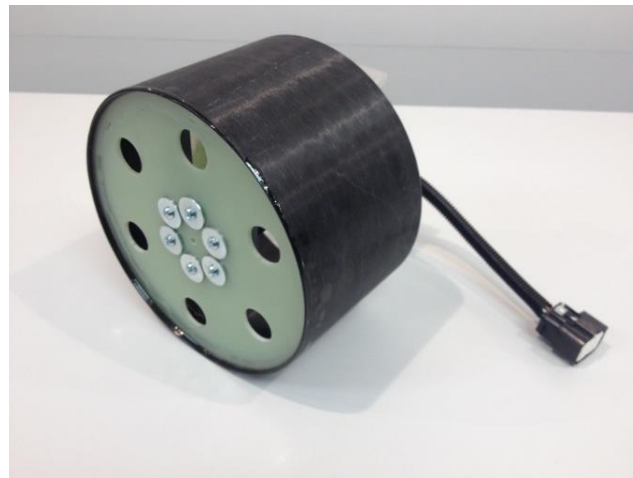


Figure 6 – Final Wheel Design Without Tread. Above shows the second generation wheel design without tread applied yet. The motors are mounted and there is a waterproof connector attached to the leads from the motor.

Next was to apply the desired tread pattern to the tire. A two-part urethane rubber mix was selected for the tread design as it can be molded to any shape. The rubber featured a shore hardness of 70A – the same as a typical tire tread. This would ensure the treads have the same flexing qualities and frictional coefficients as a normal automotive tire. Below shows the construction process of the tire tread.



(7.1)



(7.2)



(7.3)



(7.4)

Figure 7 – Rover Tread Construction Process. Above shows the essential steps in creating a wheel. Figure 7.1 shows each mold block section being CNC'd, Figure 7.2 shows a completed mold box, Figure 7.3 shows one of the first molds being removed from the box, and Figure 7.4 depicts one side of the rover's tread completed.

The process of creating a tread took roughly nineteen hours per wheel (allowing the rubber to cure). This technique results in a durable wheel that can be changed to whichever tread pattern is needed.

Description of On-board Electronics. The electrical subsystem of the rover distributes power to all of the actuating and moving parts of the rover. This system includes the motors, motor controllers, servos, servo controller, on board computer, all sensors, cameras, power supply, wiring, shielding, and weather proofing.

Sensors on board the rover allow the operator to analyze real-time data during the competition. Major sensors include a voltage sensor, a current sensor, an accelerometer, and a GPS unit. A voltage sensor in parallel with the battery pack determines the battery capacity by directly correlating the voltage reading to the amount of charge left. The current sensor, a CS-100A, is a Hall Effect current sensor for DC current flow and it will be used to measure specific currents throughout the system such as between the voltage bar and the Printed Circuit Board (PCB), and between the voltage bar and the drive motors. The GPS, a 10 Hz 66 Channel GPS from Adafruit, will be used as an interface to let the driver know where the rover is on the course, as well as online viewers. The accelerometer, an ADXL345, will be used to see what type of accelerations the rover is experiencing during the competition. The rover has three cameras on board: one on the mast to gain a heading for the rover, one on the arm to focus on a target rock, and one of the front of the rover to act as a color sensor. The camera on the mast, which is elevated 50.8 cm above the rover, has pan and tilt capabilities. The mast camera is a Logitech C920 HD Pro Webcam with HD 1080p video at 30 fps. It also has a wide 78 degree diagonal field of view. The large viewing arrow and high quality video feed the operator get a better picture of where the rover can safely navigate, as well as look for rocks. These cameras will be powered by the onboard computer via USB.

Apart from the sensor system, the drive and manipulation system consists of thirteen servos and six motors. The six motors are BLWRPG24V-4200-R24 series brushless DC planetary gear

motors from Anaheim Automation. They supply a max torque of 24.78 Nm, with a rated speed of the output shaft at 175 rpm. Each of the six motors is controlled by six DC motor drivers. The driver selected was the MDC100-040101. These motors were selected from preliminary terra-mechanics calculations with a desired total torque of 10.2 N-m at 143.3 RPM

The servos selected for turning were also the same servos selected for the arm manipulation. The HS-5685MH servo is a standard ratio servo with a maximum rotation of 180 degrees. The rover electrical system, including the turning and arm manipulation has a total of 7 HS-5685 MH servos. The additional servos on the used with the arm manipulation system and the claw are the HS-5585MS for wrist rotation, HS-5565 MS for more wrist motion and HS-7954SH for the claw itself. The additional two servos that will be used on the rover system are pan and tilt servos on the mast. They are both Hitec HS-311 servos.

Estimating a segment of time, the duty cycle, to which each electrical component will be active during a one-hour run time, then applying it to the electrical properties, the required power for that component can be calculated and used in the electrical budget. An electrical budget was used to see how much power the rover would need to run for a one hour time period and then used to find an appropriate on-board power supply. Table 1 is a simplified electrical budget based on each electrical subsystem. The total energy required to run the rover for one hour is 185.36 Wh. The battery is a K2B24V10E lithium iron phosphate battery (LiFeP04) with a capacity of 9.6 Ah and a DC voltage of 25.6 V. A LiFeP04 battery was chosen as it is cheaper, has a faster discharge rate, and has negligible mass gains over a lithium ion battery. With three batteries in parallel, the onboard power supply will produce 692.2 Wh, allowing the rover to operate for 3.72 hours.

Along with the power supply and the electrical components, proper wiring and shielding needs to be done to protect the electrical system from failure. With the K2B24V10E batteries, the electrical system could expect current spikes from the motors drawing high levels of current to increase the torque. To accommodate for potential high current spikes, as well as high voltage, specific gauge wire was used. Using the American Wire Gauge (AWG) chart based on the possible current spikes, wire gauge was able to be chosen for different sections of the electrical system. For the wire coming directly off the battery, 6-gauge wire was selected based on the AWG chart. A 60 amp inline fuse was also placed here as a safety feature.

For each of the motors and four turning servos, a large connector is used to allow for motor and servo removal in case of failure. Along with the connector as part of the wire harness, an aluminum wire braided sheath will be used to protect important electrical components from electromagnetic interference and radio frequency interference. Because the braided sheath is metal, it has to be grounded. A plastic wire loom was placed around the sheaths to provide weather protection as well as to keep the wire harness organized.

The last part of the electrical system is the use of the Printed Circuit Boards (PCBs). There are two, two layer, 3x4 inch boards sandwiched on top of each other with the lower board interfacing directly with the Arduino, and the upper board interfacing with the power supply and all the servo connections. PCBs were used to add a simplified central hub to save space and condense the amount of wiring needed on the design. Not only does the PCB interface directly with the Arduino and servos, but it also is where all of the different sensors are located. Another important electrical component being used on the PCB is the DC-DC converter. The DC-DC converter takes the 25.6 volt power supply and regulates it to the 5 volt power supply that all of the sensors and servos use on the PCB. A continuity test showed that the PCB has all of the proper connections, and the PCB has now be integrated into the rover's electrical system.

<i>Section</i>	<i>Number of Electronics</i>	<i>Total Energy Consumed (Wh)</i>
<i>BLDC Planetary motors</i>	6	180.91
<i>Turning Servos</i>	4	1.04
<i>Manipulation System</i>	6	2.26
<i>Additional Servos</i>	3	0.49
<i>Sensors/Other</i>	5	0.66
<i>Total:</i>	24	185.36
<i>Required (Wh)</i>	185.36	
<i>Available (Wh)</i>	691.20	
<i>Safety Margin (Wh)</i>	505.84	
<i>Life Comparison</i>	3.72	

Table 1 – System Electrical Budget. Table 1 is the condensed electrical budget used for the rover electrical design. It incorporates the rover’s brushless DC (BLDC) motors, servos, and any other additional electrical components that require power. A life comparison is the equivalent run time in hours.

Implemented Manipulator System. The manipulation system of the rover is an important system for the success of the rover mission because a large part of the competition is having the capability to pick up various rocks on the course. The rocks that the rover must pick up range from 2 cm to 8 cm in diameter and masses ranging from 20 grams to 150 grams. The entire manipulation system on the rover is comprised of six servos: a rotating base servo, shoulder servo, elbow servo, wrist servo, wrist rotation servo, and claw servo. The constructed arm is shown below in Figure 8.



Figure 8 – Rock Manipulating Arm. The system shown above has a total of five degrees of freedom. The five degrees of freedom will allow for a wide range of locations to pick up rocks from and it makes it easier for the operator to do so. Each of the servos has a rotational freedom of 180 degrees.

To be able to pick up rocks, the servos used in the manipulation system must be able to apply a specific amount of torque to operate and move with the rock. Because the arm has to lift a maximum of 150 grams, preliminary torque calculations should be done to find a servo that will work. Equation 1 below represents a simple static torque required to move a mass on the end of a beams.

$$\sum T = 0 = m \cdot g \cdot L - T \quad (1)$$

In equation 1, T represents the torque, L represents the moment arm to which the force is applied, and the $m \cdot g$ represents the force that is applied on the end of the moment arm. The highest torque scenario is when the arm is fully extended. This is because if $m \cdot g$ is constant and L is maximized, then the torque will be highest. There will be a different moment arm at each joint and different lifting mass, resulting in different calculated torques at each servo.

Using this simple static equation, the required worst case scenario moment can be calculated at every joint of the manipulation system. The most torque the entire system will see will be at the shoulder. The shoulder torque T can now be calculated and it should be lower than it was initially calculated. From testing and further calculations it was determined that a counter weight should be used to help with the torques on the servo. With a counter weight of 725.5 +/- 1.0 g, and a moment arm length of 70.0 +/- 5 mm the maximum shoulder torque is 4.08 +/- 0.13 N.m. This worst case torque can be used to select the proper servos for the manipulation system. It should be noted that these calculations have a factor of safety of two built in to allow for dynamic angular accelerations within the manipulation system.

User Interface and Programming Background. The user requires a way to communicate with and control the components on the rover. The software system needs to meet minimum requirements that include streaming video from the rover, allow input from an operator, and communicate data between rover and operator.

The operator subsystem is the point of interaction for the user. The operator uses a Dell XPS laptop running Ubuntu 12.05, but the program can run on any debian-based Linux system. This program was written in a Linux environment and features a graphical user interface (GUI) to display information to the user. The GUI can select between different video feeds, shows a digital projection of the arm and wheel position, and shows sensor information. The GUI can be seen below in Figure 9.

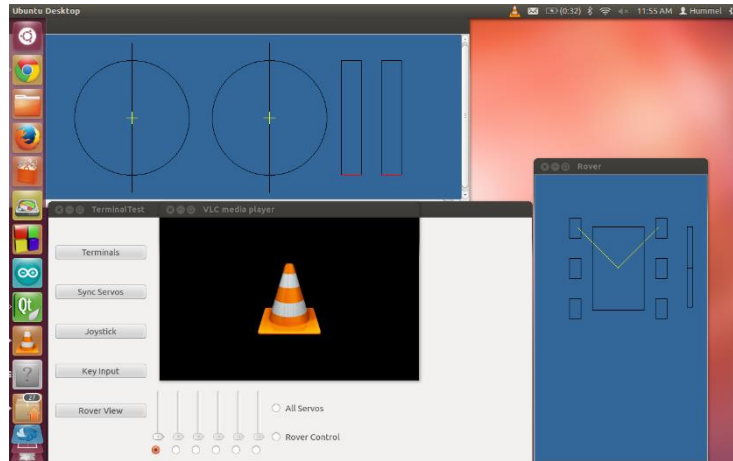


Figure 9 –Graphical User Interface for Blacksburg Operator. Above is the GUI that the operator will have available during the competition. The operator will also be able to check GPS location, battery capacity, and have access to quick debugging features such as wheel tare (if misaligned).

The best method of control input for the GUI is through an Xbox controller, which can control drive actions, arm manipulations, and video pan/tilt features. The user also has the option of using predefined arm manipulator macros that are designed to save time for the user and eliminate dangerous movements when near the rover frame when collecting a rock.

The rover has a laptop that will be running its own custom program. The onboard laptop is a Lenovo Y580 running the Ubuntu operating system. The rover program was designed using C++ and shell scripts that were designed to communicate data with the operator, pass data to the Arduino, maintain systems status, and stream video.

The Arduino is used to communicate commands to individual hardware components as well as receive data from sensors on board. The Arduino controls servo positions and motor speed as well as their direction. It receives data from GPS, current and voltage sensors, and an accelerometer. This data is sent back to the rover computer over serial and can then be passed to the operator.

The Arduino reads commands byte by byte as characters. Each data packet starts with a “*”, and each individual block ends with a “/”. The first block of each command is the identifier and corresponds to its type. The blocks following the identifier contain data to be used for a given type. The program will attempt 10 reads before continuing. Each type corresponds to its function. This could be setting a servo angle, or controlling the drive system. At the end of each main function, updates are called on each servo. The update uses an open loop proportional-integral type controller and interpolates points between a servos current position and final position, creating smooth movements for all servos.

Methods of Communication Between Rover and Operator. The communication system is designed to allow control of the rover from any location that has internet access. In this system, the operator acts as the server and the rover acts as the client. Data can be transmitted in both directions between the operator and rover. The design is used to minimize latency and bandwidth of connection. The rover will be connected to a cellular network by two 4G Verizon hotspots and the operator will be connected by Ethernet to Virginia Tech's network.

This system needs a communication protocol that is low in latency because our data is time sensitive. The UDP Protocol was chosen due to the fact that it does not require delivery confirmation, which can increase latency by at least two times. This protocol does not have any methods for checking dropped packets or knowing if the intended recipient ever received the data. If the rover has dropped or failed to send packets, they are not resent and the rover simply moves on to the next packet.

Both the rover and operator are running on dynamic IP addresses. To establish a static link the rover can be used to locate the operator, an outside service need to be used. The operator will be using a free Dynamic DNS service called Duck DNS. This service allows you link a web address, such as www.sitename.com to an IP address. The operator will automatically update the service with its current IP address. The service will then reroute any connection to rover.duckdns.org, to the operator. This is the address that Animus will attempt to establish a connection with the operator. Once the operator has received an initial signal from Animus, it will bind its address and commands can be sent back and forth.

Chapter 3: List of Technical Specifications

The Table below gives a list of key specifications.

Mass	<i>35.2 Kg</i>
Dimensions (LxWxH)	<i>98.5 cm x 72.0 cm x 46.5 cm</i>
Rated Payload	<i>18.14 Kg</i>
Maximum Speed	<i>2.24 m/s</i>
Maximum Obstacle Size	<i>Suspension Travel: 24 cm Clearance: 26 cm</i>
Operating Time	<i>3.7 Hr</i>
Drive Power	<i>25.93 Nm at 175 RPM</i>
Drawbar Pull	<i>19.23 kg</i>
Battery	<i>25.6 VDC, 9.6 Ah K2B24V10 Lithium Iron Phosphate (3)</i>
On-Board Computer	<i>Lenovo IdeaPad Y580 20994KU</i>
Communications Interface	<i>4G Verizon Hotspot (2)</i>
Software	<i>Linux-Ubuntu 12.04</i>

Table 2 - Technical Specifications. Animus’s key specifications are detailed above. Drawbar pull is the amount of tractive force in the horizontal direction from rest. Operating time may vary depending on environment.

Chapter 4: Testing Strategies Used to Determine Rover Performance

A series of tests were performed with the rover after visual inspection of the terrain features at the Johnson Space Center (JSC). To replicate the uneven terrain at JSC, a nearby construction site was selected for testing. This site featured sand, gravel, and rock obstacles ranging from 3 cm to 20 cm in diameter. The location also offered a slopes ranging from 20 of 34 percent grade. The pitch and rock diameter were incrementally increased until the rover failed to navigate the obstacle successfully three times in a row. Currently, Animus is capable of climbing a 30 percent grade hill consisting of a packed dirt/rock mix. An endurance test was also performed on site where the rover was operated in normal conditions (all rover functions active, limited heavy stress scenarios) until the batteries were depleted. From this test, a run time of 3.7 hours was achieved.

A friction test was also performed to gather coefficient of friction data for different terrains. This data will be useful for future teams so they can derive wheel forces with higher precision, and will be used for analyzing how much traction the tread will have during the competition. During these tests a spare tread was laid down and a mass was rested on top of it. At one end a force gage was attached. A diagram of this can be seen in Figure 10 with forces labeled. The static and kinetic friction coefficients were determined by using basic statics equations based on time, distance, mass, and spring scale measurements.

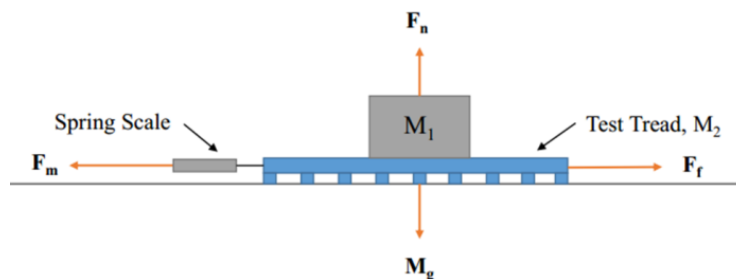


Figure 10 –Coefficient of friction test free body diagram. Above shows the free body diagram used to derive the equation’s necessary to find the static and kinetic coefficients of friction. After solving these equations, a set of unknown parameters can be measured during testing.

The soil used for testing was a mix of 2 cm gravel and loose dirt. This test will be repeated for other terrains such as sand, grass, and different density soil mixtures during May 20th to May 31st to understand the frictional capabilities of the urethane rubber on different soils. Tests have shown the rubber to have a static coefficient of friction of $.81 \pm .031$ and a kinetic coefficient of friction of $.74 \pm .038$ for the 2 cm gravel and loose dirt case.

Chapter 5: Competition Strategies

The decision was made early on that the best way to achieve success during the competition was to focus on the higher valued objectives and to regulate the available time carefully. Above everything else, the team wanted to be sure that Animus could obtain the 25 points acquired by picking up a single rock in each area and the 15 points for ending back at the Mars Hill. To ensure that Animus can succeed in completing these objectives, the team will lean on Animus’s strengths.

Animus is capable of easily traversing uneven ground and large rocks by utilizing its rocker-bogie system accompanied with carefully designed wheels. It is expected that Animus will be able to collect multiple rocks in each area. The driver will focus on collecting the more easily obtainable rocks, as opposed to the higher risk rocks, due to time considerations. The team hopes that the speed of Animus will make up for the lack of focus placed on obtaining higher point value rocks.

Chapter 6: Distribution of Funds and Current Budget

The work conducted and progress made on this rover has been possible due to the generous funds and donations made from a variety of sources. The team began with an initial fund of \$2,000 provided by the Aerospace Department at Virginia Tech, and allowed the team to begin work immediately, before receiving the main funding. Figure 11 shows the distribution of all acquired funds for this project. Approximately one-third of the money used to build the rover was provided from sources outside the competition.

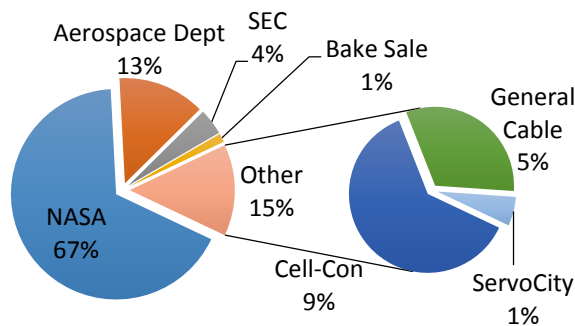


Figure 11 – Breakdown of Income and Donations. Above shows how PYREX was funded for the 2014 Robo-Ops Competition.

Fifteen percent of funding has been from our sponsors who have collectively allowed the team to save over \$2,200 in essential parts and equipment. Additionally, \$595 was given by the Student Engineering Council (SEC) at Virginia Tech, and over \$200 was raised through a bake sale.

With the current budget that was made available over the duration of this project, approximately 53% of funds were used to purchase the structural components for the rover, 23% was utilized for electrical and communications equipment, 20% was used for all the fees associated with travelling to the competition, and the remaining 4% was used for additional tools and miscellaneous items needed for the development of the rover.

Chapter 7: Public Outreach and Stakeholder Engagement

The competition focuses on both how well the rover performs and how well teams can reach out to the community. For the competition, 10% of the final score was based on how well the team could reach out to the public and make lasting impressions in the local community. To reach out to fans of the project, both Facebook and Blogger were used to provide team updates. The Facebook page, www.facebook.com/VTRover2014, was used to build up a fan base and provide short updates about the progress of the systems. Currently 428 fans are following the teams updates on Facebook. Blogger, vtrobo-ops.blogspot.com, was used to provide more detailed updates and thanks our major contributors. The team posted between one and two articles per week. Since the blogs launch, over 1,840 page views were recorded, with 435 page views in April alone.

The team sought out to find lasting relationships with companies, specifically companies that have stock invested in rover applications. Public stakeholders provided the team advanced technology for a discounted price to promote scientific advancement. Originally, the team sent out brochures to many companies with the idea of finding stakeholders. The companies that were the most inspired by the team were those that had an interest in the product. Outside of the competition and the University, Cell-con, ServoCity, and General Cable were major contributors. Cell-con, a leading manufacturer of energy solutions in aerospace and general applications, donated approximately \$1,300 of Lithium Iron Phosphate batteries and a charging station. General Cable donated \$675 of cable for the team to test and wire all of our low voltage components. ServoCity, an online retailer for many electrical components, gave the team a student discount of approximately \$125 on servos used in the arm and turning servos. These companies were very helpful in completing the rover, and PYREX is glad to have made lasting connections with the companies for future teams to use.

References

- [1] Wong, J.Y. Terramechanics and Off-Road Vehicle Engineering. Butterworth-Heinmann, 2009. Print.
- [2] Ahmadian, M., "Class Notes, Spring 2014," CRN #14813 ME 4534, Mechanical Engineering, Virginia Tech.