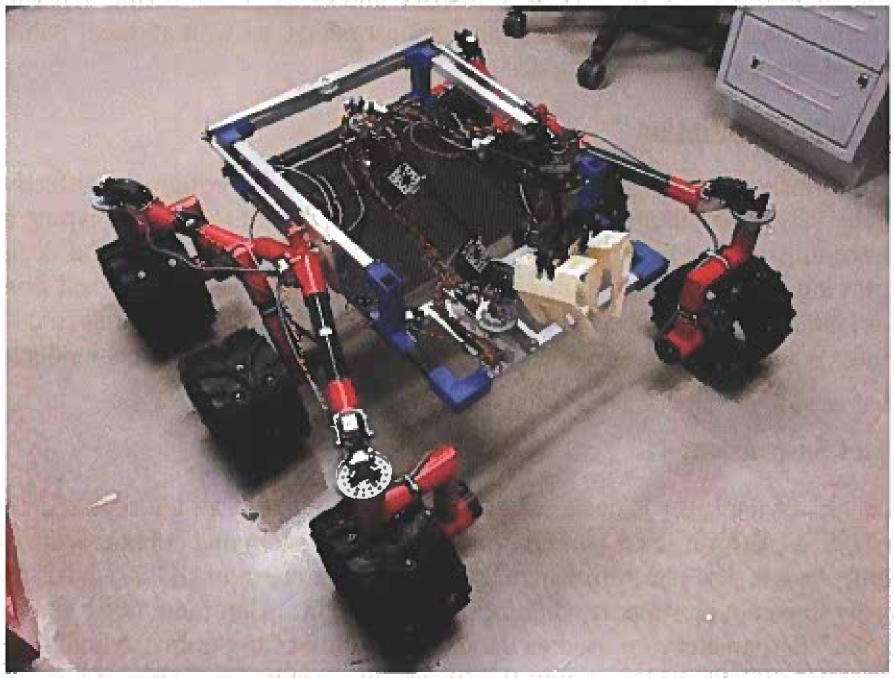
2015 RASC-AL ROBO-OPS ROVER DESIGN COMPETITION

TEAM VERTEX

FINAL TECHNICAL REPORT

VIRGINIA POLYTHNIC INSITUTE AND STATE UNIVSERITY
BLACKSBURG, VA 24060



TEAM MEMBERS

HISHAM AZ ALDEEN	JESSE PEDRONI
MIKE FULTON	DONGYUN SHIN
STEPHEN KRAUSS	RONALD SISDO
JUSTIN MARUT	AJ YOST

FACULTY ADVISOR

DR. KEVIN SHINPAUGH

AEROSPACE AND OCEAN ENGINEERING

Chapter 1: Introduction

Planetary rovers are required to withstand the challenging terrain present on celestial bodies, as well as be able to accomplish specific scientific objectives while traversing such terrains. These two primary design objectives are precisely what the National Institute of Aerospace (NIA), in conjunction with the National Aeronautics and Space Administration (NASA) have incorporated into the Revolutionary Aerospace Systems Concepts-Academic Linkage (RASC-AL) Exploration Robotic Operations (Robo-Ops) Competition. The Virginia Tech rover, named Optimus, is designed and built by eight aerospace engineering students under the faculty advisor, Dr. Kevin Shinpaugh of the Virginia Tech Aerospace and Ocean Engineering department. Team VerTex is also involved with local and national sponsorships, as well as local public outreach events to increase interest in engineering design.

Chapter 2: Systems Description

The performance of Virginia Tech's rover is evaluated through the effectiveness and efficiency of the various components in the overall design. While rapid prototyping and testing procedures were utilized due to time constraints, essential systems analysis and decisions were made by employing the analytical hierarchical process (AHP) and lessons learned from the 2014 Virginia Tech team. Computer aided design (CAD) drawings assisted in initial calculations and further planning. What follows is a detailed description of the various design components onboard Optimus. [1]

2.1 Chassis and Suspension:

The chassis of the rover is designed to sustain the weight of all the required components, as well as provide a platform for mounting the suspension system and robotic arm. Figure 2.1.1 shows the frame design. The platform where the components are mounted is a 1/16" thick carbon fiber plate, providing enough support while being lightweight. Aluminum 6061 and carbon fiber square tubes, 3/4" in diameter, are used as the main skeleton of the frame. Aluminum is used in places where drilling is required to mount the suspension system and rover arm as aluminum is easy to drill into. Carbon fiber tubes are utilized in frame regions where no drilling is required to eliminate unnecessary weight. The joints connecting the frame components are made of 3D printed ABS plastic which was cured with epoxy to increase its strength. The frame is 0.64m long, 0.43m wide and has a mass of 3.1 kg.[2][3]

Figure 2.1.1: A CAD model of the rover chassis. Above is the chassis model of the rover Optimus showing the carbon fiber plate, Aluminum and carbon fiber tubes and ABS joints

Optimus has a six-wheel rocker bogie suspension system, providing high stability while the rover is traversing various terrains. A rocker-bogie system allows the wheels that are not traversing objects to remain in contact with the ground at all times. CAD drawings and FEA analysis methods were used to determine an efficient design that is both lightweight and strong. The 2014 team used fiberglass for the rocker-bogie arms, which proved to be insufficiently strong. The 2015 team concluded that circular carbon fiber tubes and epoxy-cured 3D printed ABS plastic joints were the best material choice for the suspension system. Figure 2.1.2 shows a CAD model of the suspension system.[2]

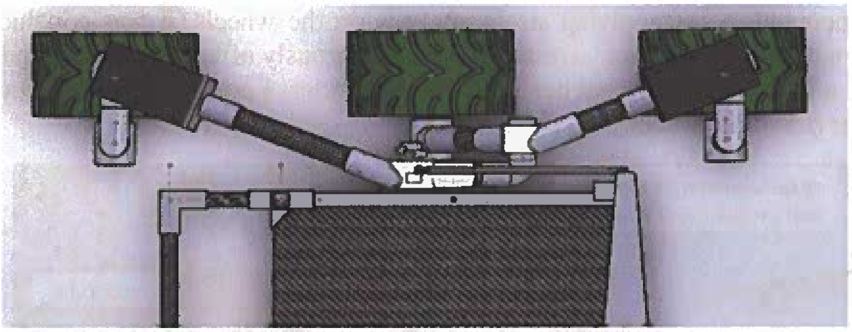
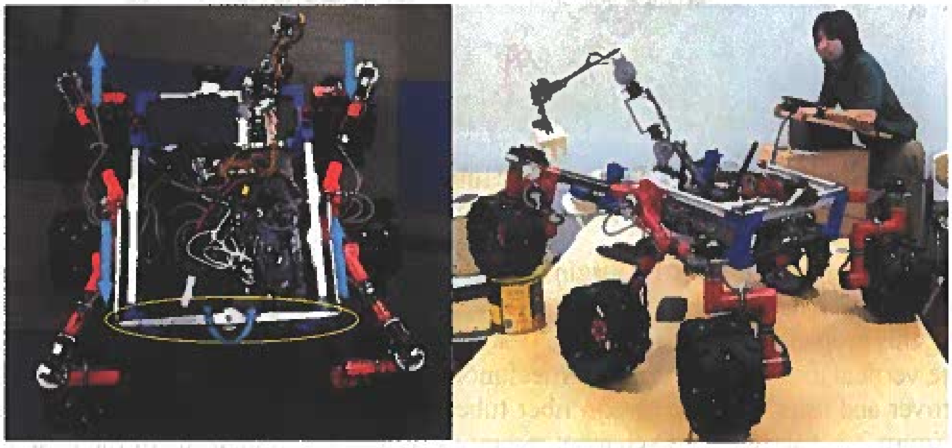


Figure 2.1.2: Rocker-bogie suspension system. Carbon fiber tubes and 3D printed ABS joints.

The differential bar seen in figure 2.1.2 is a vital part of the rocker-bogie suspension. If one of the rover wheels is raised while traversing an object, the differential bar rotates as seen in figure 2.1.3. This rotation pushes the opposite side of the suspension system down allowing all wheels to maintain contact with ground at any time. Figure 2.1.3 also shows a view of the rover traversing an object. The rocker-bogie suspension is mounted to the chassis using a 3D printed ABS bracket and an aluminum joint.



(a) (b)

Figure 2.1.3: (a) Top view of the rover. Yellow ellipse indicates the differential bar. Blue arrows indicate the direction of the forces. (b) This shows that all the wheels contact on the ground while the front wheel stand on an object.

2.2 Drive and Manipulator Systems:

Optimus utilizes a six-wheel drive system, with 6 brushless DC motors and 4 steering servos. The servos are mounted on the front and back wheels of the rover to increase its mobility, and can rotate ±180° from the neutral position. The wheel is constructed from circular carbon fiber tubes, to which the tread is attached. The tread is molded from a urethane rubber mix and is the same off-road pattern as the 2014 team. This design was chosen using terramechanics analysis, to be discussed in the testing strategy section of the paper. To help support the forces on the wheels, small carbon fiber tubes are used as spokes, which are attached to a 3D printed ABS hub where the motor is mounted. After applying stress analysis on the wheels, it was concluded that the structure does not buckle and shear stresses do not dangerously affect the spokes and their hubs. Figure 2.2.1 is a picture of the wheel design with dimensions. Epoxy is used to secure the spoke hub to the outer rim of the wheel.

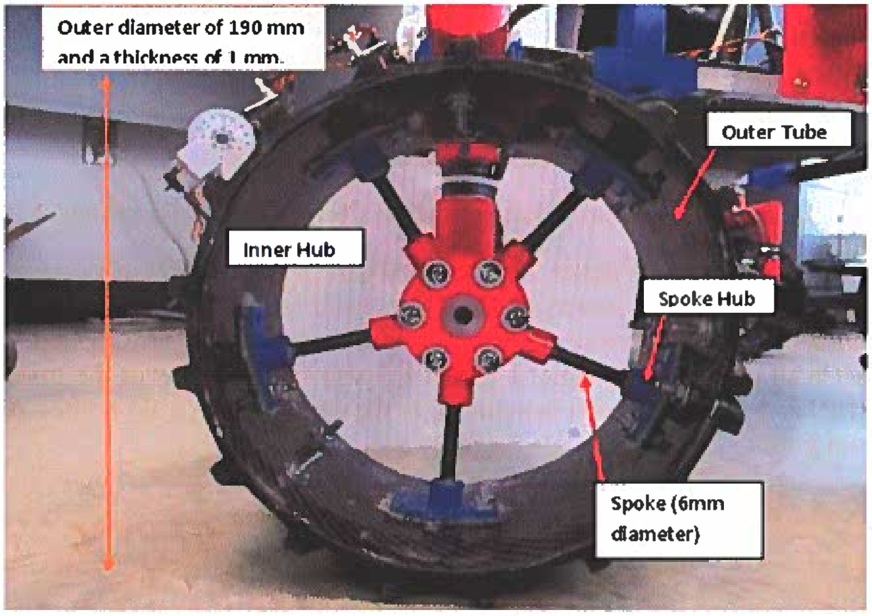


Figure 2.2.1: Rover wheel design. Carbon fiber tube for the outer rim, ABS hub and spoke hubs and carbon fiber spokes.

The wheel design of the 2014 Virginia Tech rover experienced an inward bowing problem. This placed unnecessary stresses on the wheel connections under the weight of the rover. Considering this problem, our team applied a design which aligns the wheel's drive and turn points on the same vertical axis. The C-channel wheel mount designed by the team is based on NASA's Curiosity rover and uses 4 square carbon fiber tubes with 3 ABS joints to connect the tubes in a C-shape. Figure 2.2.2 shows the C-channel mount as well as stress analysis of the design. A 7.5 kg mass was applied on the wheel mount which simulates 1/6th of the maximum allowed rover mass of 45 kg.[2]

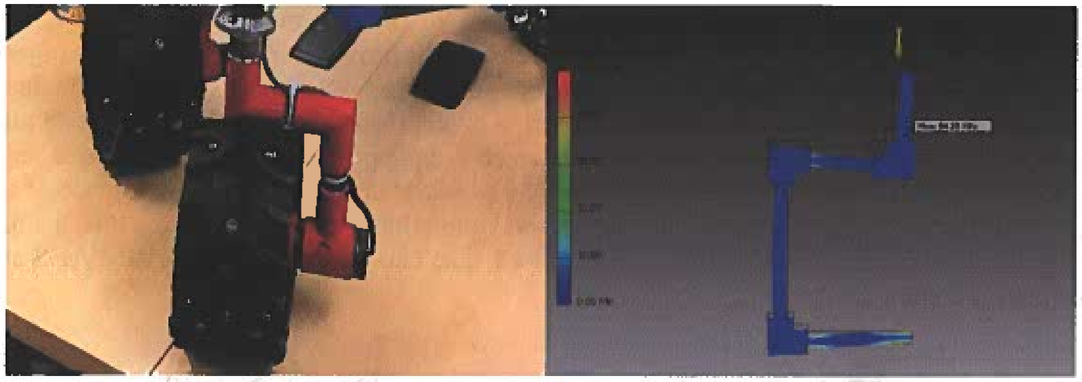


Figure 2.2.2: C-channel wheel mount. Left shows the wheel alignment, right shows the stress analysis results.

The manipulator system onboard Optimus is a five degree of freedom (5 DOF) robotic arm with a claw. The design of the manipulator system focused on the lifting mechanism that handles the weight of the arm and any object it grabs as well as the arm reach and rotation abilities. The arm design consisted of 5 servos representing the 5 DOF system. Like the turning servos, the arm servos have ±180° rotation capabilities. The arm consists of a shoulder with 2 DOF, an elbow with 1 DOF and a wrist with 2 DOF. The shoulder and elbow are connected with two carbon fiber rods, while the elbow and the wrist are connected with a single carbon fiber rod. One concern the team had was the stiffness of the carbon fiber rods and whether they would bow when the arm is lifting weight. Tests were conducted where the arm grabbed objects of similar weight to the rocks during in the competition and manipulated around the 5 DOF while carrying the object. The results of these testes led to the conclusion that bowing is not an issue for the carbon fiber tubes. Figure 2.2.3 shows the arm design along with its reach and DOF.

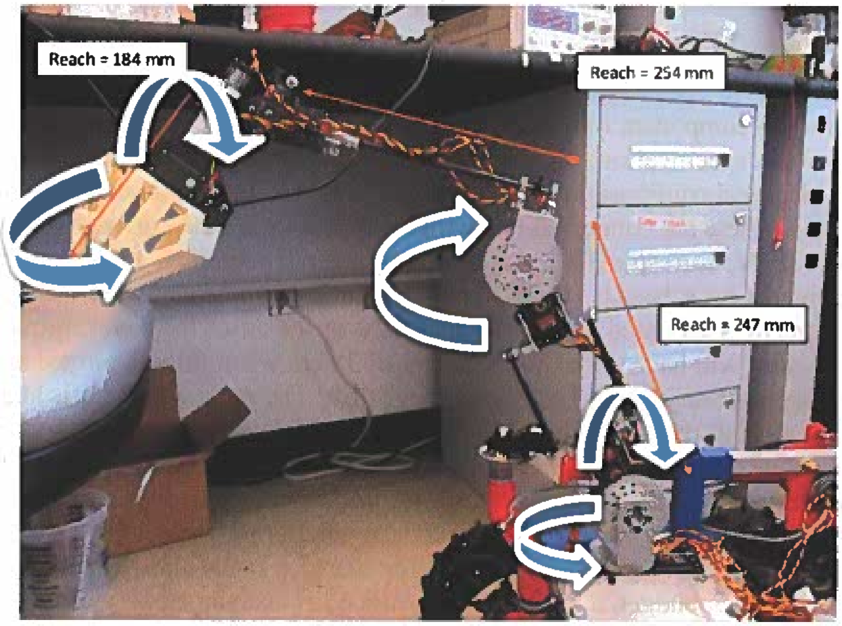


Figure 2.2.3: The final manipulator system for Optimus. Arm reach, DOF and claw

The claw represents the acquisition mechanism of the manipulator system. The main driving factor in the design of the claw were the specifications provided by the NIA for the objects to be collected during the competition. After examining last year's claw design, the team determined that a gripper system is easier for grabbing object than a pincer mechanism. A parallel gripper kit acts as the base for the claw operation, which is equipped with a 222 oz.in. torque servo to allow pinching of collected objects, if necessary. The initial maximum opening distance of the gripper was less than size of some rocks used in the competition. To accommodate this, a small opening was introduced when the claw is fully closed. The claw is made of 3D printed ABS and can be seen in Figure 2.2.4.

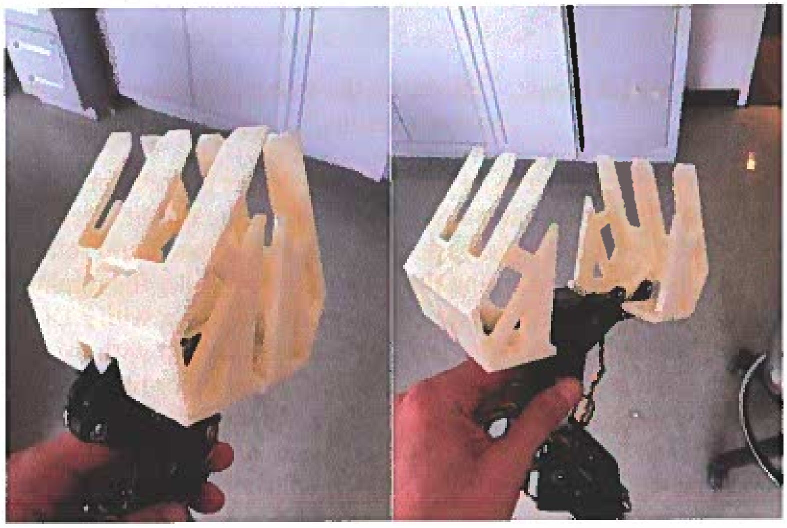


Figure 2.2.4: Optimus' claw design. ABS claw and gripper kit in retracted and fully extended modes.

2.3 Rover Electronics:

Each electrical component onboard Optimus has a specific power consumption based on its current and voltage specifications as well as the duty cycle of the component. Team VerTex optimized a new electrical configuration for Optimus. Two Li-PO 6-cell rechargeable batteries act as the power supply. These are connected in parallel and provide a total current capacity of 16 Ah and a voltage of 22.5 V, corresponding to 360 W of power. To simplify the electrical layout of Optimus, two printed circuit boards (PCBs) were designed. Two cameras are used onboard the rover. The first camera is mounted to a retractable mast at the aft of the rover, providing a wide field of view. The mast will have a maximum height of 38 cm when fully deployed and will have 360 degree panning capability as well as 30 degrees of tilt. The second camera is attached to the arm, which will be used during acquisition. The resolution of the two cameras can be changed on demand using the control code. A Raspberry Pi 2 serves as the rover computer, and a Cradlepoint 3G/4G broadband router is used to establish a connection to the rover. Optimus is also equipped with a GPS unit and a microphone to provide audio stream during the competition. Figure 2.3.1 shows the PCB, battery and Raspberry Pi 2 computer. Table 1 shows the electrical budget of the rover. As seen in the power budget, a factor of safety of 2.43 is maintained between the total energy required and available. This is important because electrical specifications and power calculation are performed assuming ideal components. In reality, there exist uncertainties in the number specifications of the electrical components, in addition to inefficiencies in the operation of these components.[4]

Figure 2.3.1: Optimus' battery, Raspberry Pi 2 and PCB.

Table 1: The final electrical components of the rover. Values in this table are based on electrical properties of the components, and efficiencies (uncertainties not included). This budget is a theoretical representation of the electrical system on the rover that led to determining the requirements for the power supply.

Optimus Electrical Components

Component	**Count**	**Voltage (V)**	**Current (mAmp)**	**Total Current (mAmp)**	**Total Power (W)**	**Duty cycle (min)**	**Total Energy Required (Wh)**
Drive motors	6	11.1	1500	9000	100	60	100
Steering servos	4	9.6	400	1600	15.4	60	15.4
Arm servos	3	6	1,000	3,000	18.0	10	3
Claw servos	3	5	500	1,500	7.50	45	5.63
Scoop camera	1	5	160	160	0.80	45	0.60
Main camera	1	5	160	160	0.80	60	0.80
4G/3G USB broadband router	1	12	1500	1500	18	60	18
GPS unit	1	3.3	205	205	0.677	60	0.677
Microphone	1	5	300	300	1.50	60	1.50
Accelerometer	1	3.3	0.01	0.01	$3.3*10^{-5}$	60	$3.3*10^{-5}$
Raspberry Pi 2 rover computer	1	5	500	500	2.5	60	2.5
						Required (Wh)	148
						Available (Wh)	360
						Factor of Safety	2.43

2.4 Control and Communication Systems:

The Robo-Ops competition requires teleoperation of the competing rovers. While the rovers are at Johnson Space Center (JSC) in Houston, Texas, operators control the rovers from their respective college campuses. To achieve uninterrupted and efficient rover control, the programming and communication systems must provide a stable platform with ease of control and efficiency. As previously mentioned, a Raspberry Pi 2 was chosen as the rover computer. It provides various general purpose input and output (GPIO) pins, USB and Ethernet connections in addition to sufficient computing power to handle all the required software commands. A Cradlepoint modem is used for communication with the rover. This modem supports Verizon 4G and 3G services and is able to switch between the two. One concern that faced the communication team is the bandwidth at the site of the competition, which may lead to insufficient connection with the rover. To prepare for this, a few measures of precaution where integrated in the control code, including variable frame rate for the video feed as well as the ability to switch off unused cameras. The USB cameras used on the rover have the capability of compressing the video feed using H.264, which reduces the bandwidth usage dramatically. Currently the video feed experiences about 0.2 seconds of latency. When the rover is in Texas, however, latency will increase due to the distance between the rover and control center.

Both UDP and TCP internet protocols are used for network communication. The choice of one over the other is done dynamically based on the importance of the command. Our team determined that this is the best strategy to avoid any flaws due to latency in the connection. Additionally, a LogMeIn Hamachi VPN is used to establish a direct tunnel between the rover and the control computer through Virginia Tech's firewall. The VPN also assigns each device a static IP address to relieve the control code from handling a dynamic IP address that changes occasionally. The Hamachi interface establishes an automatic, pre-configured, connection with the Raspberry Pi 2. Figure 2.4.1 shows the layout of the communication subsystem of Optimus.[5][6][7]

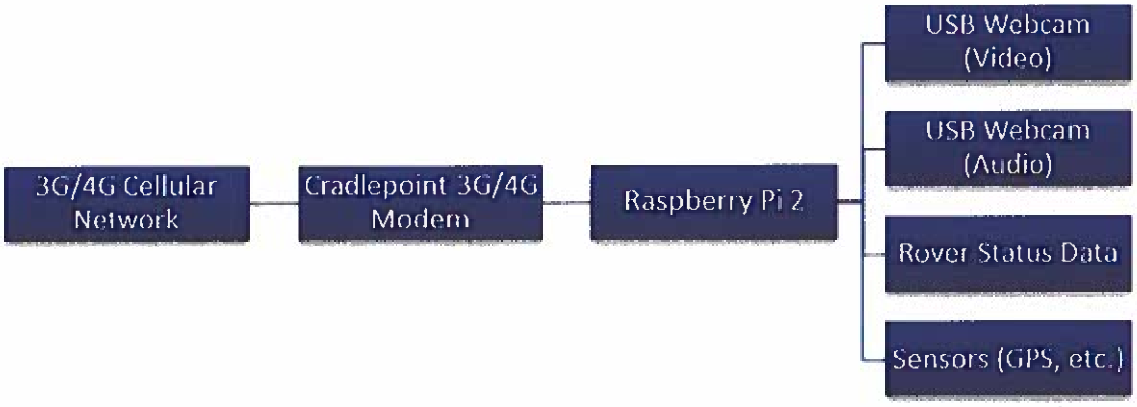


Figure 2.4.1: Rover communication data flow.

As for the control interface, Python is used as the main programming language for the operation of Optimus. Python has easy to use networking libraries as well as native support libraries for the Raspberry Pi. The code layout of the rover is shown in figure 2.4.2 where the command sending, receiving and rover settings subsections are detailed.[8]

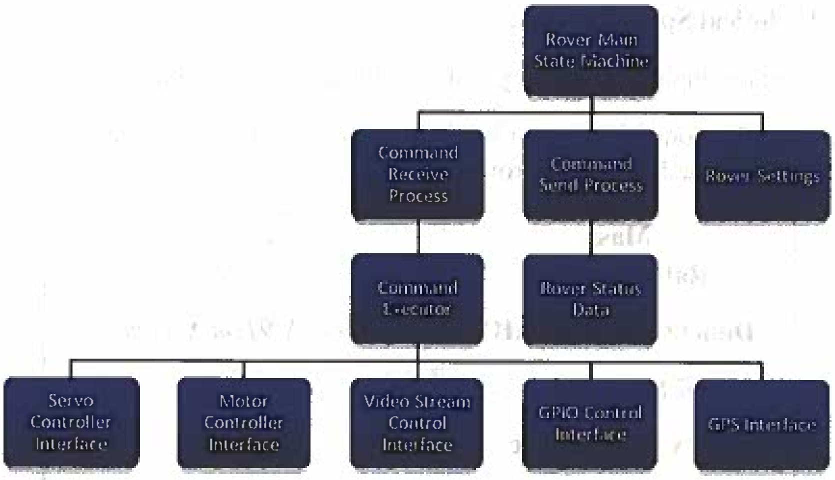
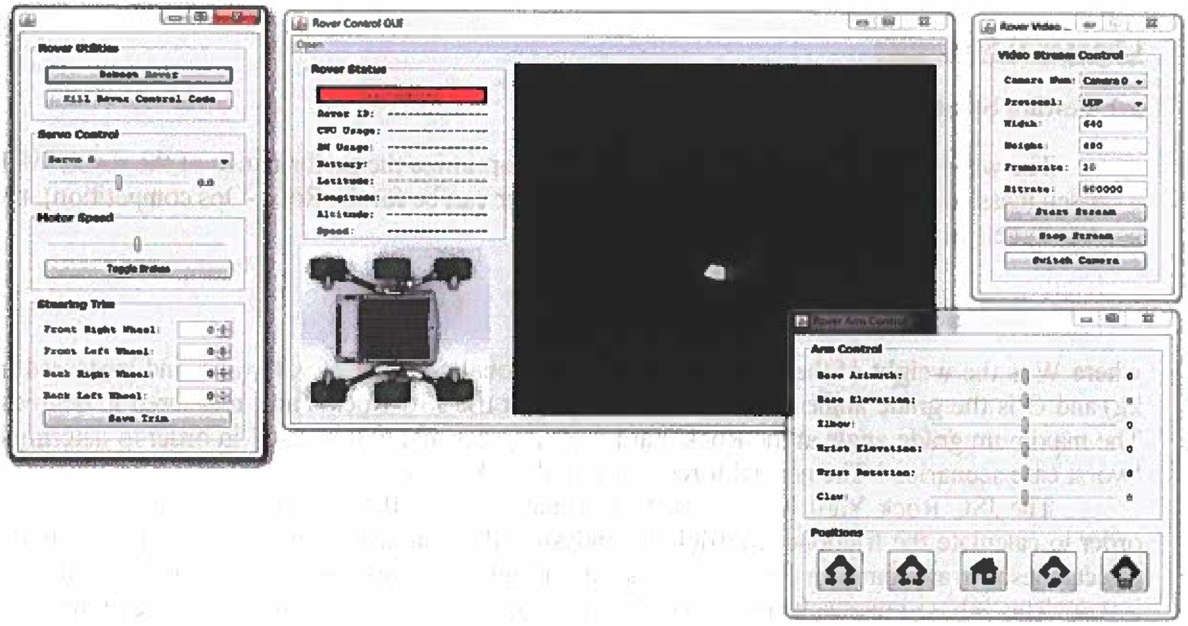


Figure 2.4.2: Optimus onboard code layout

Another important aspect of the control interface is the Graphical User Interface (GUI), which is the method of communication between the rover and the operator. The GUI was created using the JAVA programming language, as JAVA provides many networking and interface libraries in addition to convenient development environments. The interface consists of multiple windows broken up by function, including: arm control, video stream control and status display windows. The GUI is shown in figure 2.4.3.[8]



Servo 0
0.0

Front Right Wheel: 0
Front Left Wheel: 0
Back Right Wheel: 0
Back Left Wheel: 0

Rover ID: ----------------
CPU Usage: ----------------
RM Usage: ----------------
Battery: ----------------
Latitude: ----------------
Longitude: ----------------
Altitude: ----------------
Speed: ----------------

Camera Num: Camera0
Protocol: UDP
Width: 640
Height: 480
Framerate: 15
Bitrate: 800000

Base Azimuth: 0
Base Elevation: 0
Elbow: 0
Wrist Elevation: 0
Wrist Rotation: 0
Claw: 0

Figure 2.4.3: Rover control code windows (GUI).

2.5 Complete Technical Specifications:

The table below highlights the key features of the rover Optimus.

Table 2: Main specifications of the rover Optimus. Operating time is based on the power factor of safety and can vary based on the environment

Mass	*25 kg*
Rated payload	*30kg*
Dimensions (LxWxH)	*95cm X 91cm X 41cm*
Max speed	*1.5 m/s*
Max obstacle size	*10 cm*
Operating time	*2.43 hr*
Drive power	*35.28 N.m at 175 RPM*
Battery	*22.5 VDC, 8 Ah, 6 cell Li-PO battery (2)*
Rover computer	*Raspberry Pi 2*
Communications interface	*Cradlepoint router with Verizon 4G/3G*
Software	*JAVA, Python*

Chapter 3: Strategies

3.1 Testing Strategy

The wheel diameter and tread were chosen to optimize the performance of the rover. With a chosen mass of 45kg (the maximum mass that a rover can be for the Robo-Ops competition), the normal force can be calculated using Equation 3.1:

$$N = W * \cos\theta \qquad (3.1)$$

where W is the weight of the rover (using a gravitational constant of 9.81 m/s^2 and measured in kg) and Θ is the grade angle of the various terrains at the JSC Rock Yard, measured in degrees. The maximum grade angle at the Rock Yard is 30 degrees and will be used in order to determine 'worst case scenarios.' The normal force calculated is 382.3 N.

The JSC Rock Yard is comprised of primarily two different terrains; sand and rock. In order to calculate the frictional coefficient, analysis will be done on sand and gravel to study the effects these terrains have on the rover. For sand, a rough estimate of the static frictional coefficient is 0.60. This is based on results from an off road tire on sand. The static frictional force of the same tread on gravel is given to be 0.60 as well. Using Equation 3.2, the frictional force can be calculated from:

$$Fr = N * \mu \qquad (3.2)$$

where N is the normal Force, measured in N, and μ is the frictional coefficient. The static frictional force calculated for both terrains (as they have the same frictional coefficient) on a grade angle of 30° is 229.4 N. The highest normal force will be when the rover is on even terrain and therefore would equal the weight. At this case the static frictional force is 264.9 N.

Based on the results of the 2014 Robo-Ops rover design, the velocity achieved was relatively high compared to other rovers in the competition and therefore will be chosen for this year's design. The maximum velocity desired is 1.5 m/s. Using Equation 3.3:

$$RPM = \frac{(Max\ Velocity)*60}{\pi*2*R} \qquad (3.3)$$

where R is the radius of the wheel, measured in m. The revolutions per minute needed can then be calculated. In this case, our rover will operate with 6 wheels and a radius of 10 cm per wheel in order to traverse the 15 cm rocks found in the Rock Yard. Therefore, the RPM will be 143.2.

In order to calculate the required torque of each motor, the various forces applied to the rover must be determined. For this particular case, it will be assumed the rover is traveling up a grade of 30 degrees on gravel, at a maximum velocity of 1.5 m/s and acceleration of 0.75 m/s^2. The rolling frictional coefficient for an off road tire on gravel is roughly 0.022. Using Equation 3.2, where N = W *Cos(grade angle), the frictional force was calculated to be 8.4 N. In order to calculate the total force needed, Equation 3.4 was used:

$$Total\ F = Fr + W * Sin(\theta) + M * a \qquad (3.4)$$

where Fr is the frictional force at an incline of 30 degrees, measured in N, W is the weight of the rover, measured in kg, Θ is the grade angle, measured in degrees, M is the mass of the rover, measured in N, and a is the acceleration of the rover calculated to be 0.75 m/s^2. The total force was calculated to be 262.9 N. Using Equation 3.5 to calculate torque:

$$Torque = Total\ F * R \qquad (3.5)$$

measured in Nm, and where R is the radius of the wheel design, measured in m. The torque needed for the desired parameters was calculated as 26.3 N m. That is the total torque that must be produced by all the drive motors in order to accelerate the rover 0.75 m/s^2 at an incline of 30 degrees. To determine the required torque of each motor, the total torque was divided by 6, the total number of drive motors. The total torque per motor, therefore, is 4.4 N m.

Calculations were performed in order to determine whether a wheel will slip due to application of a high torque. The Max Total Torque (MTT) value is defined as the torque that will cause the wheel to slip in the various conditions and is measured in Nm. Using Equation 3.6, the MTT was calculated:

$$MTT = W * \mu f * R * \#\ Drive\ Wheels \qquad (3.6)$$

where μf is the static coefficient of friction of sand. Figure 3.1 shows the MTT as a function of the diameter of the wheel, and the total torque needed to accelerate the rover 0.75 m/s^2.

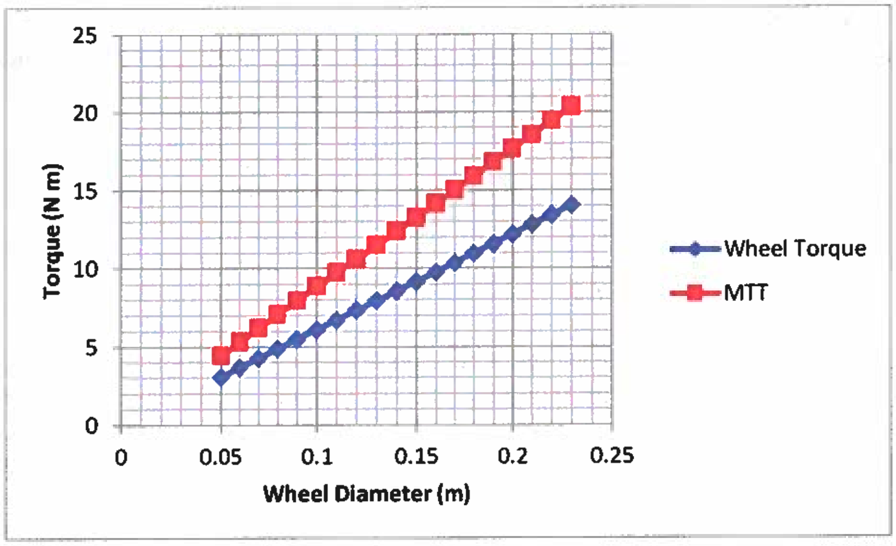


Figure 3.1: Total torque needed and Max Total Torque of the Rover as a function of the Diameter of the wheel. The figure above shows that increasing the wheel diameter affects the torque needed as well as the MTT.

Figure 3.1 shows that a smaller wheel diameter will lower the possibility of a wheel slipping. This is due to the fact that as diameter increases, total torque needed begins to separate from the max total torque that will cause slippage. Figure 3.2 shows the torque needed as a function of time to achieve max velocity for two cases; an incline in gravel of 30 degree and traversing through the sand.

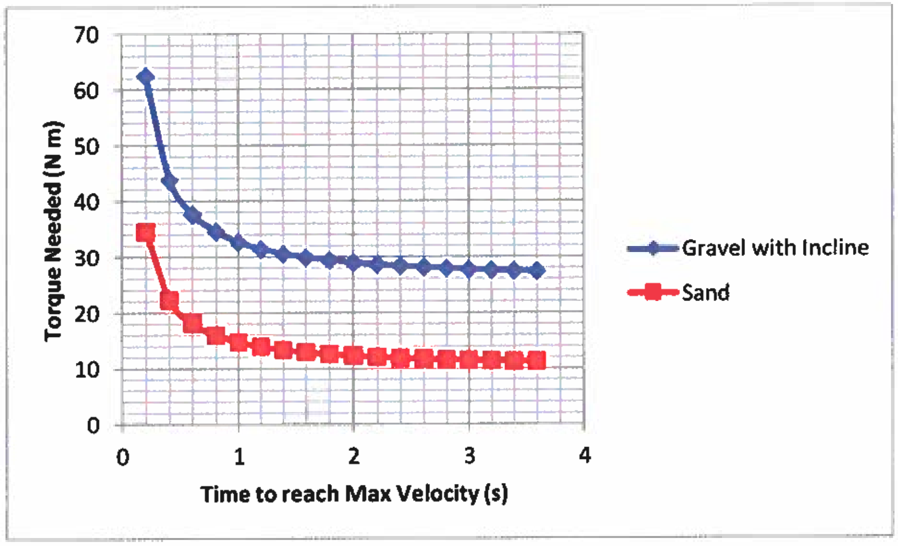


Figure 3.2: Total torque needed plotted as a function of the time to reach max velocity. The figure above shows the how increasing the time, indirectly lowering the acceleration, lowers the torque needed to reach the maximum velocity, for both a 30 degree incline in gravel and roving through the sand.

Applying a factor of safety of 1.3 to the total torque each motor must produce to traverse the gravel incline, the torque needed per motor for a 6 DC motor design is 5.7 N m. With inefficiencies in motor design, a Brushless DC motor (BLWRPG172S-24V-4200-R24) with a peak torque of 5.88 N m was assumed to be enough for the application desired.

3.2 Overall Competition Strategy:

The goal of the chassis design was to make it simple and lightweight. Using 3D printed ABS plastic for the joints ensured ease of manufacturing. The use of carbon fiber tubes for the skeleton ensured sufficient strength while keeping it lightweight. The aluminum square tubes were used for quick integration of other rover components, such as the manipulator and suspension systems.

The suspension system was chosen to ensure maximum stability while traversing terrain. Using a six wheeled rocker bogie system ensures sufficient stability, as well as having 6 drive motors for maximum speed. While this suspension system has more mass due to the extra wheels, the team felt that stability during the competition was a necessary trade off.

The manipulator arm uses thin carbon fiber rods to reduce mass, while maintaining strength and rigidity. The five DOF design allows for maximum range of motion in front of the rover. The claw has pointed prongs in order to extract rocks that may be in areas that are not open. It was designed with sufficient space between the prongs to sift through dirt and sand.

3.3 Mission Control Center Operation Strategy:

The rover will be controlled from the Virginia Tech Center for Space Science and Research control room. A computer with multiple monitors will be used, and three members of the team will man the control room. Of the three members, one will be at the controls driving and collecting rocks. The second team member will assist with driving by focusing on the video feed for obstacles and rock locations. The final member of the team will keep track of timing and offer navigation suggestions based on time remaining, known rock locations, and ensuring bonus points are awarded for tasks like collecting at least one rock from each terrain.

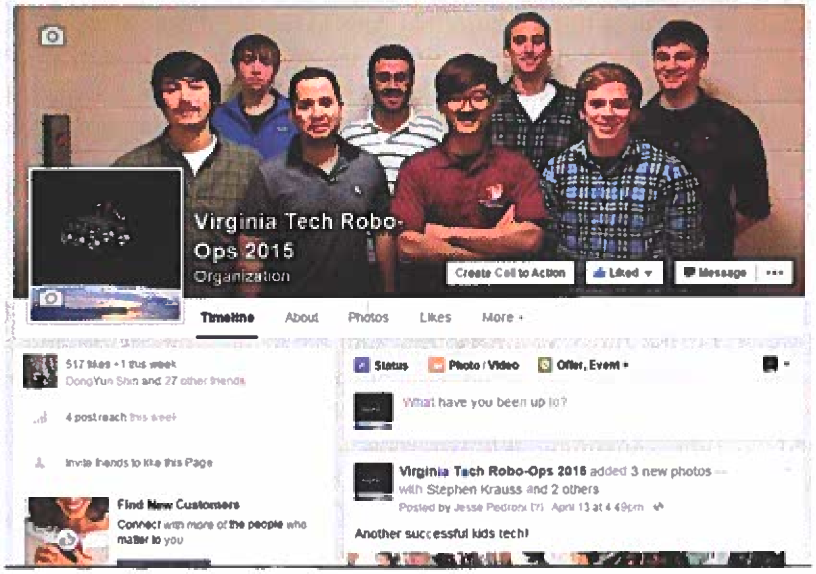
To ensure the control center members work well with each other, they will man the control center in a real competition simulated environment while the rover is being tested. The navigator will have the ultimate decision making authority regarding the rover's path. The navigator will talk closely with the driving assistant to help locate rocks. The driving assistant with talk closely with the driver to ensure an optimal approach path to the rock acquisition location. The main programming lead will be in the control room if any problems arise during the competition.

Chapter 4: Team VerTex Budget

The sponsors of the 2015 Virginia Tech Planetary Rover design team were the National Institute of Aerospace, the National Aeronautics and Space Administration, Dassault Systemes SOLIDWORKS, the Virginia Tech Aerospace and Ocean Engineering department, and SRC. NIA and NASA provided the team with a total of $10,000, VT AOE provided a total of $4,000 and SRC provided a total of $500. A total of $3000 was allotted for travel expenses, while the rest of the funds were used for rover construction. There will be some leftover construction funds, which will be used by next year's design team.

Chapter 5: Public Outreach

The team created a Facebook page and blog site, displaying the progress of the rover to the public. Figure 5.1 is a screenshot of the team Facebook page. An article will be published in the Aerospace and Ocean Engineering newsletter in the near future about the team's progress this year, as well as on the Virginia Tech Center for Space Science and Engineering Research, with the intent to generate public interest in the team. The Virginia Tech Bioinformatics Institute sponsors a program called 'Kid's Tech University.' In this program, children interact with various science, technology, engineering, and mathematics (STEM) exhibits from the Virginia Tech student community. The team volunteered for 3 of these sessions, but only participated in 2, as weather conditions called for the first Kids Tech event to be cancelled. During these events, the participating team members displayed and answered questions concerning various rover components, including 3D printed parts, control and communication architecture, and mechanical assembly of the rover.



Virginia Tech Robo-Ops 2015
Organization

517 likes • 1 this week
DongYun Shin and 27 other friends

4 post reach this week

Invite friends to like this Page

Find New Customers
Connect with more of the people who matter to you

What have you been up to?

Virginia Tech Robo-Ops 2015 added 3 new photos — with Stephen Krauss and 2 others
Posted by Jesse Pedroni · April 13 at 4:49pm

Another successful kids tech!

Figure 5.1: Team VerTex Facebook page.

Chapter 6: Conclusion

The mechanical sub-system has made the rover lightweight and strong, significantly reducing the mass of the rover, about 15kg, compared to Virginia Tech's previous rover. The electrical sub-system has designed an efficient layout for the electrical components, making use of custom circuit boards to simplify and organize all electrical connections. The communications sub-system has implemented a simple, yet robust connection between the rover and control center and implemented command and data streams for control of the rover. Finally, the programming sub-system has developed, organized, and documented code to establish control of the various rover components and provide a simple graphical user interface for teleoperation. The team believes that it has made the best use of all available resources to design and construct a competitive rover and looks forward to competing at the Johnson Space Center in June.

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