RoboUtes Final Technical Report for NASA RASC-AL Competition 2013

Nicklaus Traeden, Michael Bills, Matthew Monahan
The University of Utah, 201 South Presidents Circle, Salt Lake City Utah, 84103

The RoboUtes are; Nicklaus Traeden, Michael Bills, Abhijit Boppana, Matthew Monahan, Aditya Pandey, John Henry, Jon Davies, Anh Luong, Enoch Lee, Daniel Henshaw, Hunter Grayson, Aaron Wernerehl
With Professor Mark Minor PhD

Abstract. The University of Utah RoboUtes robotics competition team intends to compete in the National Institute of Aerospace's RASC-AL Exploration Robo-Ops planetary rover competition. Competing teams must build rovers that can collect samples spread over NASA's Planetary Analogue Test Site at Johnson Space Center in Houston, Texas. To achieve the objectives of the competition, the multidisciplinary team will field a sophisticated teleoperated rover called. This rover utilizes an innovative simple passive suspension system, a versatile robust sample collection effector, modern construction materials, and industry leading manufacturing techniques. A daughter buggy system works in tandem with the main rover to facilitate faster sample collection and scouting. Signal from the user interface will travel to the rover through a Verizon Wireless USB modem. The rover will broadcast a WiFi signal to allow for user communication to the daughter robot. Local control of the rover is also possible for testing and outreach purposes. The RoboUtes team has engaged the community by promoting the excitement of space exploration. This has been achieved through a dynamic and expanding online presence, volunteer work, mentoring programs, hands on demos, and by cooperating with local partners and organizations. To accomplish this work the RoboUtes team has used a wide array of available technical resources and has leaned on the experiences of the previous rover designs

INTRODUCTION

The NIA Revolutionary Aerospace Systems Concepts - Academic Linkage (RASC-AL) Robo-Ops competition represents an analogue to the challenges of actual planetary rovers. Planetary rovers handle extreme terrain and environments to perform scientific tests on collected samples. To simulate this, the competition rovers will have to navigate four different variable terrain fields and collect colored rocks, forcing the rovers to have a robust suspension and drive assembly and versatile sample collection system. Existing surface rovers rely on either a radioisotope thermoelectric generator or solar panels for power. Because of this, the rovers usually have slow movement speeds so path determination efficiency is critical. To maintain this level of critically with higher power competition vehicles, a one hour time limit is established. The RoboUtes team has designed a capable terrain traversal and sample acquisition platform designated COLE Mark IV, or Cellular Operated Land Explorer Mark IV (referred to variously as "COLE", "the robot", or "the rover" throughout this documentation.) The COLE Mark IV platform features a sturdy passive suspension system and a dynamic four degree of freedom manipulator arm. The RoboUtes team hopes to mitigate the time constraint by utilizing a daughter robot to gather easily-obtainable samples and scout hard-to-get samples for the main rover. The RoboUtes team feels that this addition largely separates their design from previous rovers and is a valid step forward in planetary rover systems, as it allows for a larger area to be explored in the same time period for relatively low additional power, weight, and economic cost.

SYSTEM DESCRIPTION

Chassis Design and Drive System

COLE MK IV is designed to be a highly capable off-road exploration vehicle. Durability, speed, and power are the primary objectives of the mobility system. This is a system designed to explore an entire planet in an hour, and leave no brightly-colored stone unturned.

Some Technical Specifications:

Rated Payload	50 kg (distributed)
Max Speed	1 m/s
Peak Torque	115 N*m
Obstacle Size	0.25 m (rated)
Operating Time	6 hours
Total Mass	43 kg (estimated)
Arm Reach	0.66 m
Arm Lift	1.5 kg

Chassis

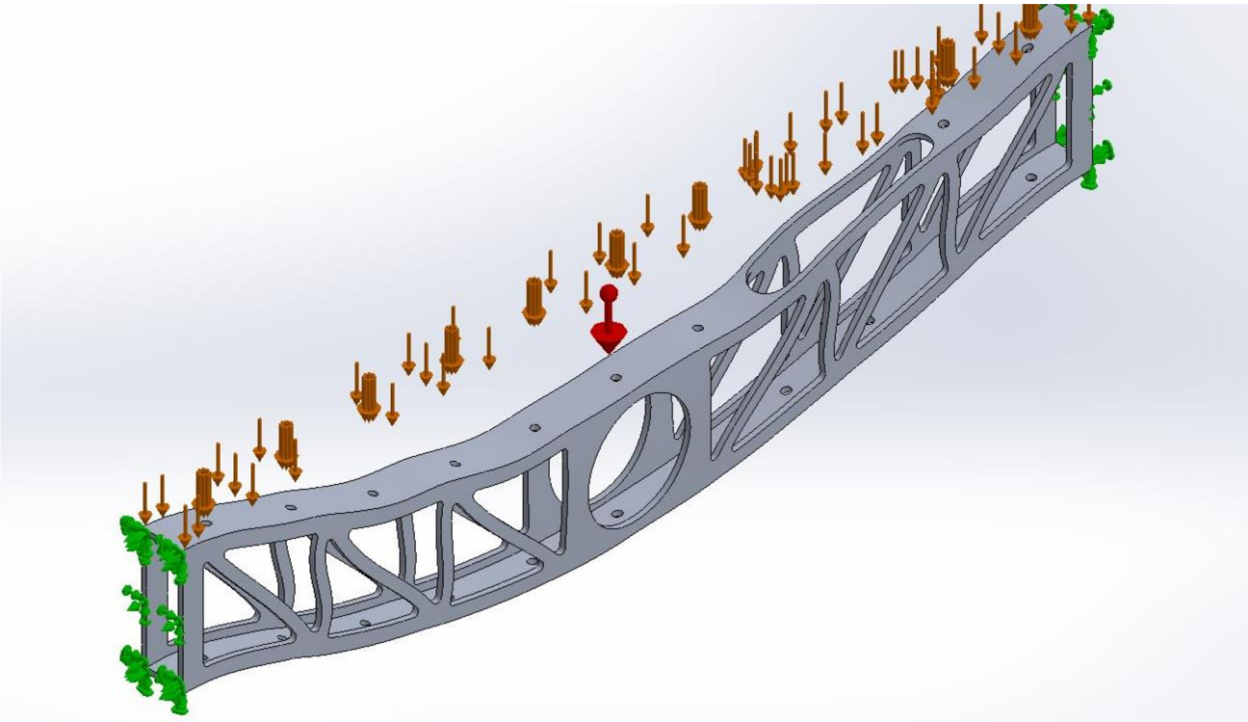


Figure 1: Deformation Simulation on Chassis Component

COLE MK IV's main structural components are made of 6063 architectural aluminum, a material known for its favorable weight to strength ratio, machinability, and corrosion resistance. Aluminum tubing was cut to length on the vertical milling machine, and holes for bearings, fasteners, etc. were added. An OMAX Precision Abrasive Waterjet Cutting Machine was used to remove excess materials from the tubing and baseplates. The chassis sections were TIG welded together. The chassis easily supports its own weight (as well as the occasional weight of a child-sized passenger), and has withstood a significant amount of abuse during testing. A polycarbonate bash plate is fastened to the bottom of the chassis and vacuum-formed structures cover the front, back, and tops of the rover.

Spine

Figure 2: Exploded View of Spine Assembly

The main body of the spine is a 2.5” polycarbonate tube, with a wall thickness of 0.125”. LDPE and acrylic spacers, steel compression plates, and hex bolts are used to create a spine assembly that stays tight in the axial direction, but still allows the two chassis sections to roll relative to one another. Nylon blocks are used to support and locate the spine tube inside the chassis wall section. The interior of the spinal tube provides a safe and convenient cable chase for the various wires that pass between the two sections. The spine allows COLE to traverse large obstacles while maintaining four-wheel contact with the ground, making it extremely capable on rough terrain without adding significant cost or complexity.

Wheels

COLE features four 16” diameter wheels, with pneumatic tires and a knobby, off-road style tread pattern. The hubs are custom-machined to mount to the axle assembly. Pneumatic wheels are not necessarily optimal for planetary missions, but for the purposes of Robo-Ops they provide excellent traction, vibration damping, and durability. Foam-filled versions of the same units would be able to perform in any atmosphere (or lack thereof), and may be employed in future projects.

Figure 3: Wheel Assembly

Motors
Each wheel is actuated by its own dedicated 24V DC gear motor, with a 47:1 ratio. These motors are hard-mounted to the rover chassis, and coupled to an axle and bearing assembly to transmit power to the wheels. Feedback is largely visual, though the user does have access to data about the current draw from each motor, which can be used to diagnose stall situations or other problems.

Control System
The drive system is controlled by an Arduino Mega, augmented with an Arduino Ethernet Shield, four Pololu Simple High Power Motor Controllers, and four current sensors. The user generates commands for the left and right side motors independently using dual analog sticks. Driving both sides forward or backward will move the robot in that direction. Creating a speed differential between the two sides allows turning while moving. Running one side forward and the other in reverse allows the rover to turn in place.

Manipulator Arm
For a telerobotic system to be considered truly capable of exploring other worlds, that system must have some way of physically interacting with the planetary environment. It has been demonstrated in past Robo-Ops forums that a very simple manipulator arm can collect rock samples effectively. However, modern planetary exploration has moved beyond the mission objective of “collect rocks”, and as such the RoboUtes have elected to field a manipulator arm capable of completing significantly more advanced tasks. COLE Mark IV features an arm with four degrees of freedom, the specifics of each are discussed below. With a maximum reach of approximately 0.66 meters, the arm has an operating area of about 1.3 m^2. This workspace is mapped in Cartesian three-space, with the origin placed at the center of the turntable axis. Movement in the x-y plane is controlled by a turntable, and movement in y-z is controlled by some combination of the shoulder, elbow, and wrist joints. Using this convention, the arm can be easily dispatched to any point in the operating area using a simple ordered triple of coordinates, i.e. P = (x,y,z). When the arm is not being used, it is stowed away in a storage position that protects it from excessive loading during transit.

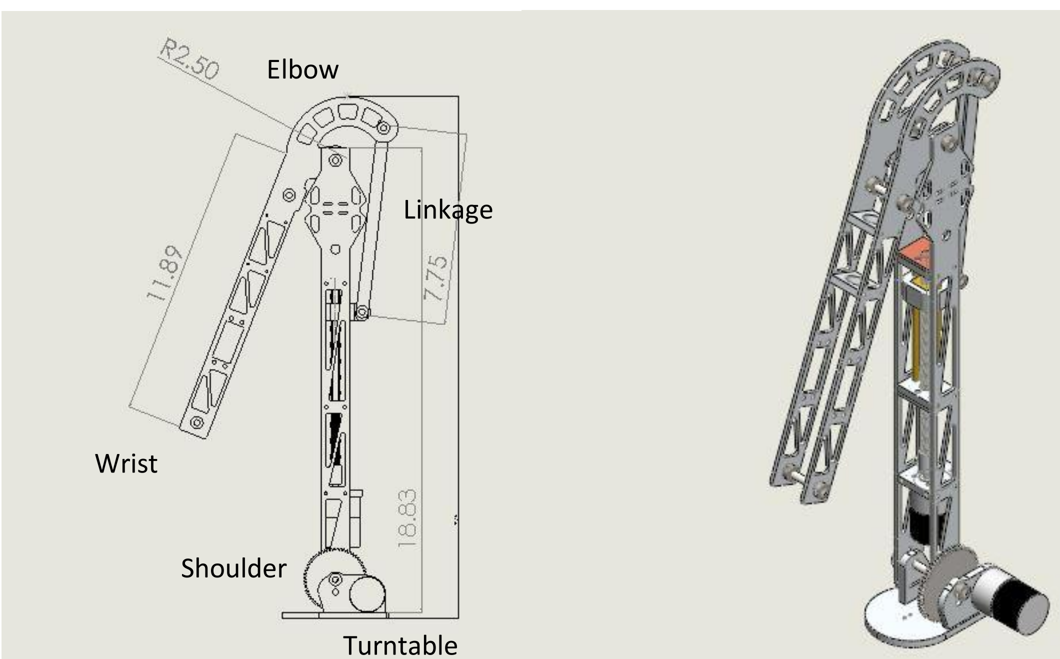


Figure 4: Manipulator Arm

Structure

The manipulator arm's main structural components were cut from 6061 0.125" aluminum, using an OMAX Precision Abrasive Waterjet Cutting Machine. Brackets and cross bracing were similarly cut from 0.25" material, with drill and tap operations being performed on the vertical milling machine. Rotating connections are constructed using 0.25" stainless steel shaft, riding in bronze bushings where applicable. 3D printed components were manufactured on a home-built 3D printer, using primarily PLA plant-based plastics.

Turntable

The arm's yaw movement (x-y plane) is controlled by a 29:1 12V DC gearmotor actuating a 30:1 worm-drive turntable, for a final drive ratio of 870:1. The nature of the worm gear makes this joint impossible to backdrive, a major improvement over previous servo-based designs. The steep gearing makes the turntable extremely powerful, and capable of making accurate, minute changes of angle for completing delicate tasks. Position data is acquired using a potentiometer connected to the turntable output shaft. The turntable is theoretically capable of continuous rotation, but for simplicity's sake will be limited to 360 degrees. Maximum slewing speed is approximately 2 RPM.

Shoulder

The shoulder's movement is controlled by a 3000:1 24V DC gearmotor, actuating a 4:1 spur gear transmission, for a final drive ratio of 12,000:1. The shoulder joint is self-locking, due to the extremely steep gearing. The transmission design is modular, and the RoboUtes manufacture their own custom spur gears in-house, making it possible to re-gear the shoulder in the field for more power or more speed as needed. It is likely for the Robo-Ops forum, gearing will be reduced to 1:1 or 0.75:1, for quicker operation. Position data is acquired using a potentiometer connected to the shoulder output shaft. The shoulder has an angular operating range of approximately 200 degrees, and a maximum rotating speed of approximately 2 RPM (as currently geared).

Elbow

The elbow's movement is controlled by a 29:1 12V DC gearmotor, actuating a 12:1 lead screw, for a final drive ratio of 348:1. The lead screw interacts with a four bar linkage to actuate the elbow joint, which also adds a small amount of variable mechanical advantage. This design allows the elbow motor to be divorced from the elbow joint, shifting the weight of the motor closer to the shoulder, decreasing the moment applied to the shoulder joint. Position data is acquired using a hall-effect rotary encoder- on startup, the system self-calibrates using a pair of limit switches. The elbow has an angular operating range of approximately 114 degrees, and a maximum rotating speed of approximately 2 RPM.

Wrist

The wrist's movement is controlled by a 6V analog servo, actuating a 1:1 spur gear transmission. The transmission design is modular, and the RoboUtes manufacture their own custom spur gears in-house, making it possible to re-gear the wrist in the field for more power or more speed as needed. The wrist does not add any unique solutions to the arm's operating area, but the ability to approach a sample from different angles has proven to be invaluable in past years Robo-Ops forums. For example, the wrist can be used to approach a recessed object from directly overhead, or a partially concealed object from below. The wrist relies on the servo motor's internal potentiometer positioning routine for feedback-visual confirmation is used to verify that the servo has, in fact, moved to the requested position. The wrist has an operating range of 180 degrees, and a maximum rotating speed of approximately 60 RPM.

Gripper

The gripper's movement is controlled by a 6V analog servo. The gripper uses two 3D-printed fingers rotating relative to one another to interact with the environment and collect samples. The fingertips have hardpoints which allow for the installation of various modular grip pads, for which development is still ongoing. Simple designs rely on compliant foam for sample retention, but more advanced designs involving Force Sensing Resistors also show promise. The integration of FSR fingertips would allow for pressure-based feedback, which would make it significantly easier to grip and retain a sample. As of this writing, gripper feedback is handled by the servo motor's internal potentiometer positioning routine and visual confirmation. The gripper has an operating range of 90 degrees, and a maximum rotating speed of approximately 60 RPM.

Control System

The manipulator arm is controlled by an Arduino Mega, augmented with a Pololu Dual Motor Driver Shield, a Pololu Simple High-Power Motor Controller, an Arduino Ethernet Shield, and the RoboUtes' proprietary Servo Amperage Handler. The Arduino manages each joint with a feedback loop, matching the joint position to a desired input position. These desired input positions are generated on the GUI side. The user has the option of using direct joint control sliders or the more advanced inverse kinematic three-space vector control to generate commands- either way sends the same data type to the Arduino, simplifying coding and saving bandwidth. The GUI also features special arm macros for automating repetitive tasks, such as returning rocks to the sample collection bin, or deploying/stowing the arm. This control scheme creates a system that is both easy to use, and computation/bandwidth efficient.

Vision System

COLE uses three separate camera systems to relay visual information from the field back to Mission Control. The buggy also features a dedicated camera for aid in its own navigation and sample collection, as well as to serve as an advance scout for COLE. All four of these video streams are broadcast simultaneously, with the option to prioritize bandwidth to one camera or another for optimum viewing.

Stereovision

COLE features two Microsoft HD5000 cameras mounted on its front fairing. These cameras are used in concert with one another to allow three dimensional stereovision viewing. Data from these cameras can be used to reconstruct a 3D rendering of the operating area of the arm. From this rendering the user can easily determine the Cartesian coordinates of a sample, and direct the manipulator arm to retrieve it. Additionally, this added perspective makes the rover significantly easier to steer accurately, as distances to obstacles and objectives can be determined very intuitively by the user.

Arm Camera

A SANOXY USB Webcam is attached to the manipulator arm. This camera aids in sample acquisition, especially in determining what commands need to be given to the gripper to successfully grasp an object. Additionally, the fact that this camera is attached to a fully articulated arm makes it an ideal camera to use for self-diagnosis of problems, or general assessment of the situation around the rover.

Boom Camera

Figure 5: Boom Mechanism and Camera

An ACTi KCM-5611 2MP IP camera is mounted at the rear of the rover on an articulated scissor boom. This boom allows the camera to lower itself in transit, but deploy to a higher vantage point to view the surrounding area. This camera is also equipped with a tilt system, to make it easier and safer to drive the rover up and down inclines. The boom camera features 18x optical zoom capabilities changing the focal range of 4.7mm up to 84.6mm. This camera also has a high level of detail and color making this camera ideal for spotting samples or other objects of interest.

Compression

Getting high fidelity video streams from COLE back to Mission Control is by far the most bandwidth-intensive procedure performed by the rover. The boom camera uses MJPEG-4 Compression to transmit video using low bandwidth. The boom camera's compression is all done online through ACTI's algorithms and then hosted on a local IP that Mission Control can reach through the router. The stereoscopic system is a little more complicated in that it will take two video feeds, combine them into one stereoscopic feed, then transmit that back to the Command Center. The vision systems for the buggies are significantly simpler than what is being used onboard COLE. Each buggy has one front facing camera whose feed it will compress using MJPEG-4 and host on a local IP. The Command Center can access this feed through the same method used to access the feeds onboard COLE.

Power Systems

Battery

COLE is equipped with a 24V, 20AH lithium iron phosphate battery. Charging and discharging battery management circuitry is located on the battery to ensure safe operation at all times. This battery enables COLE to engage in high-speed "stunt roving" for several hours or slower, more introspective and scientific roving for even longer.

Voltage Regulation

Due to the diverse electronic systems onboard the rover, COLE require voltages other than the provided battery voltage. High-efficiency programmable voltage buck boost regulators provide 19 volts and 12 volt rails for the various computers, cameras, and actuators. These Mini-Box DCDC-USB power convertors are both USB and remotely programmable and can also give status information if needed. Other required voltages are provided using simple adjustable regulators that provide similar efficiency but do not provide the feedback available in the main rails.

Protection
A 20 amp resettable circuit breaker is wired in line with the battery and provides both normal and emergency shutoff capabilities. The LiFePo4 batteries which are easily swappable are fitted with Anderson quick disconnects and wired with care to prevent short circuits or a “hot” chassis situation. Other power connections are soldered and heat-shrink covered to ensure a safe quality connection.

Control and Communication System

Modem
COLE communicates through Verizon’s 4G LTE network, as specified by the competition rules. This connection results in fairly high bandwidth but also relatively high latency given the distance back to Utah. The Novatel Wireless USB551L USB Modems are fully powered by the router and do not require external antennas to operate at the NASA Mars analog site. A nice feature of these modems is that they can be easily secured, allow for high throughput, and can send SMS alerts relating to their status back to the Command Center.

Router
The onboard router is a Cradlepoint MBR1200B. This router is loaded with useful features such as load sharing, failover, and the ability to email Mission Control status data about its connection. The router allows remote access into the majority of COLE’s systems, quick diagnosis of issues, and the ability to perform status checks of mission-critical systems. The router’s ability to easily manage multiple Verizon modems’ is one of its major benefits, and one of the primary reasons it was chosen for use in the rover design.

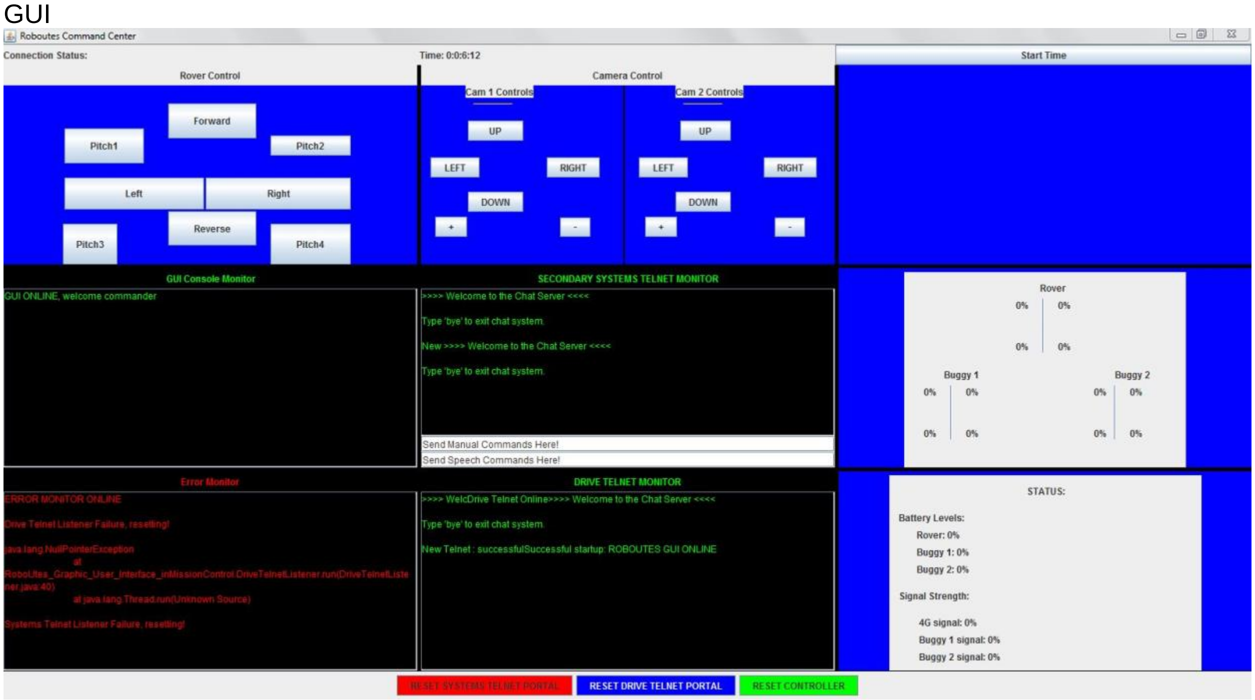
GUI


Figure 6: Graphical User Interface

COLE is operated by a custom GUI, used by students at Mission Control at the University of Utah. This Java-based platform handles all communications back and forth with the rover, as well as acquiring status data and reporting errors. Input for the GUI not only comes from the mouse and keyboard, but also from XBox controllers. The controller is the primary source for drive data and has the ability to reset various systems by pressing different buttons, allowing a pilot to quickly and easily recover a system encountering an error without needing to even touch the computer.

GSM Override
Despite robust communications and control systems, it is always a possibility that a system on the rover could encounter an error serious enough that COLE could become inoperable. To help deal with this potentially fatal situation, COLE is equipped with a completely independent GSM-based system that can restart the rover physically. In the event that these errors cannot be recovered via remote access (for example if all of COLE's communications went down) a text message can be sent to COLE that will force it to restart at its base level, the primary 24V rail. This backup system is completely independent from COLE and is powered by an independent power source.

Latency/Bandwidth
Both bandwidth and latency have proven to be significant hurdles in the development of the communications systems. To help alleviate this we have set up our router so it constantly maintains a specific amount of bandwidth, assuming it is available, connected to COLE, and sending "pings." It has become apparent that due to some property of Verizon's network, sending small amounts of data at a constant rate results in a dramatically lower ping in comparison to sending no data and then suddenly requesting some.

Buggy
COLE MK IV uses a daughter robot, known as "the buggy", to do exploration and simple sample acquisition. This buggy is equipped with a camera and connects to ROC via WiFi.

Mechanical Systems
The daughter buggy was developed to uses a track and cog system to propel itself along the ground. This system was designed and manufactured entirely in-house. The tracks allow the buggy to travel over loose sand and gravel with relative ease, which are terrain types that COLE can struggle with. These tracks proved to be a high maintenance system and a secondary chassis and drive structure is being implemented. This new structure uses four wheel drive operation similar to COLE. The buggy uses a scaled version of the gripper and wrist used on COLE to collect samples, with a small sample bin located within the reach of the wrist.

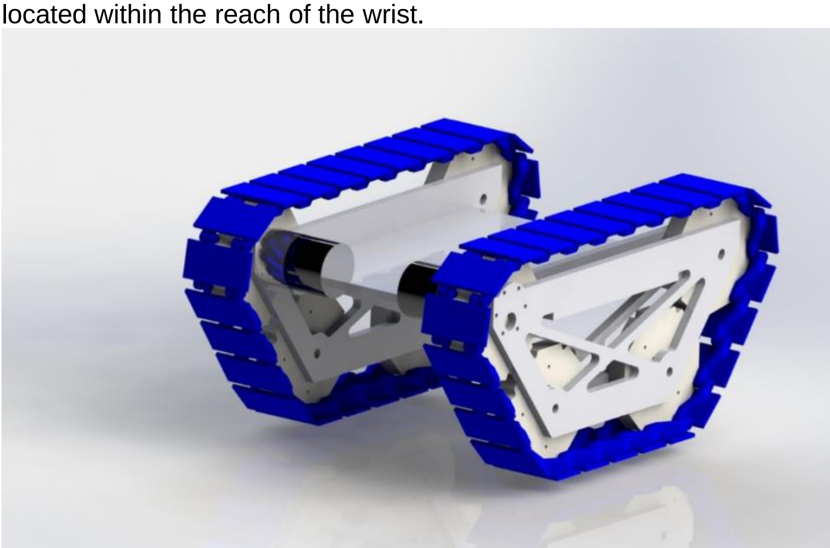


Figure 7: Buggy Chassis

Electrical Systems
The buggy's movement is controlled by four 6V DC gear motors. The gripper and wrist are actuated by 6V analog servos. The buggy is powered by a 7.2V LiPo battery.

Communication Hardware and Software
The buggy uses a Raspberry Pi as its primary computer. This computer's main responsibility is to communicate with COLE over WiFi, receiving commands and sending feedback, especially video. Motor and servo control are handled by an Arduino Mega, augmented with a Pololu Dual Motor Driver Shield. Steering is accomplished via simple tank drive, naturally.

TESTING STRATEGY

Mathematical and Software Simulation

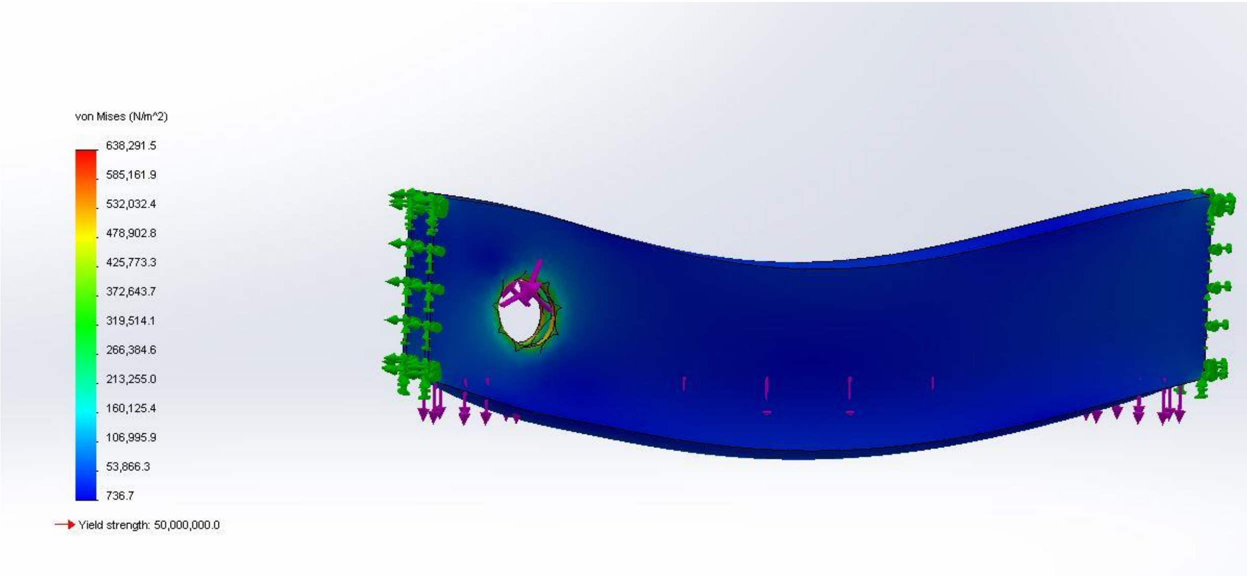


Figure 8: Stress Concentration Simulation

When a new idea is introduced in the RoboUtes Lair, the first wave of testing is done with a pen and paper. Elementary laws of mechanics, dynamics, or electronics are used to do quick, back-of-the-envelope calculations to determine if an idea is worth pursuing. Ideas that make it past this stage are modeled on the computer and tested using simulation software to identify their design envelopes. For a mechanical part, this might be a stress simulation. For a computer program, this might be a bandwidth test.

Proof of Concept
Before any serious amount of time or money is invested in an idea, the RoboUtes like to manufacture a proof of concept prototype. This prototype is often little more than a toy, a plywood cutout of a CAD part created to get a feel for the reality of that part, and identify what is right and wrong about it for the next design. Many designs die at this stage, but those that make it through emerge as a much more well-thought-out designs on the other end.

Prototype Testing
Prototype testing involves a working model of the final product. This prototype is generally "bench tested," that is, tested in isolation from other components to ensure that it works well. Components may

cycle through this stage many times, being designed and redesigned iteratively until the optimum solution is found.

Full Testing

Once a component has been shown to work well independently, it is integrated into COLE for a full system test. This is often where the most complicated problems are found. Strange interactions between different systems require time and attention to solve, and as such, testing of full systems is critical to developing stable final products.

The Robo-Ops competition has a relatively demanding timetable, and the RoboUtes do not have extensive monetary resources. Because of this, the full testing of components must often be limited to protect irreplaceable components. For example, the drive motors, in addition to being expensive, currently have a 6-8 month lead time to replace. As such, to some extent, the true potential of the platform has not been fully explored, and may never be. Every component is tested to perform at least to its minimum requirements with a safety factor.

Testing Results

Attending a large number of EPO activities has had the added benefit of rigorously testing our drive system at the hands of children. We have found that at full power COLE will climb almost any obstacle including rocks bigger than its tires and inclines greater than 45 degrees. The rover will even attempt to climb walls, usually flipping itself in the process.

Access to rapid prototyping technology has aided our testing strategy integration greatly. Multiple revisions of the arm have been made from laser cut wood which have led to a much more robust aluminum version.

COMPETITION STRATEGY

Overall Philosophy

The RoboUtes have observed in the past that the most successful teams at Robo-Ops are the teams that can cover a lot of ground quickly. In an effort to be one of those successful teams, the RoboUtes have constructed a very mobile robot, capable of traveling quickly in any area of the rock yard, including the treacherous lunar crater and boulder field. Having one or more buggy assistants will further improve the COLE system’s ability to access the field. Reaching a large number of rocks means a large number of chances to pick up rocks, which will hopefully result in a large number of rocks collected.

Diagnostic Capabilities

Another quality of successful teams is having an operational rover during the time of the competition. In order to diagnose computer problems quickly and efficiently on the field, the RoboUtes have invested in a dedicated LCD monitor and wireless mouse/keyboard to interact directly with the rover’s onboard computer. This saves time compared to having to remotely connect to the computer from a laptop, and will hopefully streamline any last-second adjustments that need to be made on the testing day or on field diagnostics.

The Game Plan

In the event that COLE MK IV is the heaviest robot in the competition, the RoboUtes competition strategy will be to drive around and pick up rocks, more or less. The Mission Commander will decide on a rough itinerary of spots on the field to visit before the competition begins. From a high level COLE will explore the hill and rock yard initially and then move to the lunar crater while the buggy explores the sand pit. This rough itinerary will be followed unless an object of interest is spotted and a detour is ordered. Upon discovering samples, the arm will be deployed and up to 5 minutes of attempts will be made to acquire the sample. After this time has expired, COLE will move on to another sample unless overridden by the Mission Commander for extenuating circumstances.

In the event that COLE MK IV is not the heaviest robot in the competition, the Mission Commander will review the competition streams from the teams who go before us with our Mission Control Team, and adjust the route accordingly to take advantage of this knowledge.

BUDGET

The RoboUtes pride themselves on coming up with innovative and clever solutions to engineering problems, even when it might be easier to simply solve a problem by spending a lot of money on it. Whenever possible, the RoboUtes manufacture their own hardware, write their own software, and pay their own way. A large portion of the raw materials that went into COLE MK IV were donated, salvaged, or repurposed from other projects. Many people donated their time, materials, and expertise to making this project happen, and the RoboUtes would like to express their gratitude for those contributions. A full list of contributors can be found in Appendix 1.

As of this writing, the total cost of COLE MK IV is estimated to be $5872.45 including Verizon charges through the build season. An itemized budget of major expenses can be found in Appendix 2.

EDUCATION AND PUBLIC OUTREACH

The RoboUtes are very passionate about Education and Public Outreach, striving to utilize robotic creations to inspire and educate young people in our community, and around the world. An educated and engaged public is critical to ensuring the continued development and funding of NASA, space exploration, and science in general. To help further this goal, the RoboUtes participate in a variety of one-time and ongoing community outreach events, many of which are detailed below. Also see Appendix 3 for a photo gallery of some highlights from this year's EPO activities.

Engineering Matters

RoboUtes team members partnered with the University Of Utah College Of Engineering to teach a week-long summer course called Engineering Matters. Throughout this week students learned about civil, mechanical, electrical, computer, and aerospace engineering, with each lesson culminating in a hands on-project where students applied what they had learned.

University of Utah

The RoboUtes are invited to demo their projects at a variety of University events, including Design Day, Meet an Inventor Night, Redfest, and others. COLE was also presented in front of the University of Utah Student Government to help garner additional financial and outreach assistance from our student leaders. In addition to official events, COLE was taken to public buildings such as the Student Union and Marriott Library throughout the build season, giving the team a chance to interact with the student body, recruit new team members, and get people excited about what's new in robotics and space exploration, with the added benefit of conducting field testing.

Girl Scouts of America Engineering Night

The RoboUtes were invited to demo their projects for a group of Girl Scouts, aged 8-18. The scouts were given the opportunity to drive COLE, play with the prototype manipulator arm, and learn about what it is like to practice engineering at the college level and beyond. Several female members of the RoboUtes were in attendance, providing an encouraging example for the prospective young engineers.

City Academy STEM In the City

As part of a fundraiser to improve their science and engineering facilities, City Academy invited the RoboUtes to demo their projects and give the students (and their parents) an idea of the kind of projects that the Academy's STEM program prepares them to work on in college.

Engineering Night
Engineering Night was an event put on by community organizers in Saratoga Springs, UT, to raise local interest in science and engineering. Approximately 400 people attended. The RoboUtes were available to demo the robot and field questions about science and engineering topics.

Astronomy Week
The RoboUtes partnered with the department of Physics and Astronomy to help put on Astronomy Week at the University of Utah's Natural History Museum. The RoboUtes demoed the rover, and gave physics demonstrations that helped give young people a better understanding of the vastness of space, and the challenges related to exploring it.

Bryce Canyon Astronomy Festival
In the spring of 2012, the RoboUtes were invited to the Bryce Canyon Astronomy Festival to demo COLE MK III, and help out at the stargazing parties. The RoboUtes have been invited back for the 2013 festival, and will be traveling directly from the Robo-Ops forum to Bryce to show off COLE MK IV's capabilities, and educate the stargazing public about the importance of robotics in the future of space exploration.

FIRST Robotics
The RoboUtes have an ongoing relationship with FIRST Robotics. The RoboUtes were present at the FIRST Lego League (FLL) Utah Championship and various FLL qualifier events and the FIRST Robotics Competition Utah Regional. The RoboUtes offered mentorship during the build seasons of these events, giving advice to middle school and high school student roboticists. The RoboUtes worked with the Department of Physics to build and organize a scrimmage field for the FRC competition that was open to all teams. COLE was onsite at the events to promote science and technology. Various RoboUtes members have helped out with competition judging, announcing, administrating, and other volunteer positions.

CONCLUSION

The RoboUtes have designed and constructed a planetary rover system that they are proud to be presenting at the 2013 Robo-Ops forum in June. We would like to thank the National Institute of Aerospace for this unique opportunity, and are very much looking forward to the forum.

Appendix 1: Acknowledgments

Engineering Consultants
Dr. Ken Monson
Dr. Larry DeVries
Dr. Thomas Schmid
Dr. Mark Minor
Mark Howell
Hamid Sani
Anthony Harper
Eric Keeney
Scott Stebbins

Manufacturing Consultants
Tom Slowick
Michael Knutson
Sean Patterson
Dan Bills

Places/Organizations
University of Utah
College of Engineering
Mechanical Engineering Department
WiESEL Lab
Machine Shop
Pro Shop
Plant Operations

Writing Consultants
Whitney Baum
Sarah Bell
Kendall Fischer

Appendix 2: Itemized Budget

Northern Industrial 16in. Poly Wheel and Tire	Chassis	4	$20.00	$80.00	$80
Chairs	Lab Equipment	2	$20.00	$40.00	$40
Chairs	Lab Equipment	6	$10.00	$60.00	$60
Whiteboard	Lab Equipment	1	$20.00	$20.00	$20
Computer	Lab Equipment	1	$788.00	$788.00	$788
Arduino Due	Drive	3	$49.95	$149.85	$150
Arduino Ethernet Shield R3	Drive	4	$39.01	$156.04	$156
6061 Aluminium Solid Sheet, T6 Temper, Annealed, Meets AMS QQ-A-250/11/ASTMB209 Specifications, 0.125" Thick, 24" Width, 36" Length	Chassis	1	$84.28	$84.28	$84
Architectural Aluminum (Alloy 6063) Rect Tube, 1" X 3", 1/8" Wall Thk, 6' Length	Chassis	2	$38.33	$76.66	$77
Architectural Aluminum Tube (Alloy 6063) Square, 3/4" X 3/4", 1/8" Wall, 6' Length	Chassis	1	$13.15	$13.15	$13
Moisture-Resistant LDPE Rectangular Bar 3/4" Thick, 3" Width, Lengths of 4 Ft.	Chassis	4	$6.00	$24.00	$24
Impact-Resistant Polycarbonate Sheet 1/16" Thick, 12" X 24", Clear	Chassis	5	$7.60	$38.00	$38
Corrosion-Resistant Bronze (Alloy 954) Oversize Tube, Bearing Grade, 2-1/2" Odx2" ID, 6-1/2" L	Chassis	1	$56.53	$56.53	$57
Metric One-Piece Clamp-on Shaft Coupling Steel, w/o Keyway, 12 mm X 12 mm Bore, 29 mm OD	Chassis	4	$30.57	$122.28	$122
Self-Align STL Flange-Mnt Needle Roller Brng for 12mm Shaft Diameter, 60mm Overall Length	Chassis	8	$10.72	$85.76	$86
Metric Fully Keyed Steel Drive Shaft 12 mm OD, 4 mm Keyway Width, 300 mm Length	Chassis	4	$24.34	$97.36	$97
Metric Steel One-Piece Clamp-on Shaft Collar 12 mm Bore, 28.6 mm Outside Diameter, 11 mm Width	Chassis	4	$4.06	$16.24	$16
Punch Cards	Chassis	3	$20.00	$60.00	$60
ASTM A193 Grade B7 Acme Threaded Rod, Alloy Steel, Right Hand, 3/8"-12 Acme Size, 3' L	Arm	1	$18.97	$18.97	$19
Brass General Purpose Acme Square Nut, Right-Hand, 3/8"-12 Acme Size	Arm	3	$5.94	$17.82	$18

Impact-Resistant Polycarbonate Round Tube, 3/4" OD, 5/8" ID, Clear	Arm	8	$1.99	$15.92	$16
Multipurpose Stainless Steel (Type 304/304L), 1/4" Diameter, 6' Length	Arm	1	$9.43	$9.43	$9
Black-Finish Steel External Retaining Ring, for 1/4" Shaft Diameter, packs of 100	Arm	1	$7.82	$7.82	$8
Impact-Resistant Polycarbonate Round Tube, 2-1/2" OD, 2-1/4" ID, Clear, 1' Length	Arm	1	$11.41	$11.41	$11
Pen-Style Digital Multimeter, 600 VAC/VDC Range	Arm	1	$44.98	$44.98	$45
Snap-Action Switch	Arm	15	$0.64	$9.60	$10
Force-Sensing Resistor	Arm	4	$6.95	$27.80	$28
Pololu Simple High Power Motor Controller 24v12	Arm	4	$45.95	$183.80	$184
20:1 Gear Motor	Arm	2	$39.95	$79.90	$80
Servo 7:1	Arm	1	$129.98	$129.98	$130
ServoCity	Arm	1	$39.95	$39.95	$40
Polulu	Arm	1	$70.00	$70.00	$70
Losi Worm Drive Wheel & Pinion Set	Arm	1	$9.25	$9.25	$9
Raspberry Pi (Model B)	Buggy	2	$35.00	$70.00	$70
Raspy Juice Rev. Beta Board	Buggy	2	$33.88	$67.76	$68
Edimax Wireless Nano USB Adapter	Buggy	2	$7.87	$15.74	$16
Worm Gear	Buggy	2	$9.25	$18.50	$19
Newark	Buggy	1	$70.00	$70.00	$70
3D Printing USA 3.00mm Translucent Blue PLA	Buggy	1	$34.00	$34.00	$34
Hotel (5 days)	Travel	2	$513.70	$1,027.40	$1,027
Van (10 days)	Travel	1	$374.22	$374.22	$374
Gas	Travel	1	$650.00	$650.00	$650
Dr. Minor	Travel	1	$2,000.00	$2,000.00	$2,000
Camera	Camera+Boom	1	$674.00	$674.00	$674
New Cradlepoint Router	Drive	1	$249.00	$249.00	$249
GSM Shield (Integrated Antenna)	Drive	1	$69.00	$69.00	$69
131:1 Metal Gearmotor with Encoder	Arm	2	$39.95	$79.90	$80
Dual VNH5019 Motor Driver Shield	Arm	1	$59.95	$59.95	$60
T-shirts	Outreach	1	$204.07	$204.07	$204
High Torque Servos 1501MG	Arm	4	$19.95	$79.80	$80
Projector	Lab Equipment	1	$563.99	$563.99	$564
Grade 36 Steel Sheet,0.1875"	Chassis	1	$43.89	$43.89	$44

Thick,12" W,36" L					
6061 Aluminum Sheet,0.125" Thick,24" W,36" L	Arm	1	$88.97	$88.97	$89
Coollcd 619ah 7 Inch Hd Lcd Field Monitor w/ H	Drive	1	$142.00	$142.00	$142
FAVI Wireless Keyboard	Drive	1	$21.06	$21.06	$21
Poster	Outreach	1	$25.00	$25.00	$25
AttoPilot Voltage and Current Sense - 90	Drive	1	$19.95	$19.95	$20
Smaller Cameras	Camera+Boom	2	$150.00	$300.00	$300
Registration	Travel	4	$300.00	$1,200.00	$1,200
T Switches	Drive	5	$1.49	$7.45	$7
Motors (75:1 4mm shaft)	Buggy	10	$17.96	$179.60	$180
Thumper 120mmx60mm Wheels	Buggy	10	$13.46	$134.60	$135
Motor Shields	Buggy	4	$49.95	$199.80	$200
High Torque Servos 1501MG	Buggy	4	$19.95	$79.80	$80
3D Printing USA 3.00mm Translucent Blue PLA	Buggy	1	$34.00	$34.00	$34
nick	Chassis	1	$170.00	$170.00	$170
nick (Ace 59)	Chassis	1	$34.27	$34.27	$34
nick (Micheals and Home Depot)	Chassis	1	$28.11	$28.11	$28
Jon	Previous Year	1	$670.52	$670.52	$671
Overflow From Last year	Previous Year	1	$700.00	$700.00	$700
Carbon Fiber/ Spectra Hybrid	Chassis	1	$38.50	$38.50	$39
2:1 Ratio Fast Epoxy Hardener	Chassis	1	$37.50	$37.50	$38
Phenolic Microballoons	Chassis	1	$7.05	$7.05	$7
Vertical Shaft Worm-Drive Gearbox	Arm	1	$59.99	$59.99	$60
Amico SSR-40DD DC to DC Covered Solid	Drive	2	$10.74	$21.48	$21
Verizon	Drive	2	$500.00	$1,000.00	$1,000

Appendix 3: Education and Public Outreach Photo Gallery

Figure 9: Engineering Night in Saratoga Springs

Figure 10: Girl Scout Engineering Night

Figure 11: Design Day at the University of Utah

Figure 12: City Academy STEM In the City