# RoboUtes Final Report for 2012 RASC-AL Robo-Ops

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**Abstract**

The University of Utah RoboUtes are fielding a sophisticated rover to overcome the challenges of the RASC-AL Robo-Ops Competition. This rover is equipped with a unique passive spine suspension system which allows all wheel engagement and variable chassis geometry giving the rover great adaptability and terrain traversal capabilities with minimal hardware complexity. A four degree of freedom arm is used to manipulate and gather samples. Distributed electronics packages allow simultaneous multi-platform development. Processing of each system is taken care of in its respective board with only command data packages sent from the user interface to mitigate the bandwidth constraints.

An iterative approach to the design and fabrication has been utilized by this year's team to allow for cross discipline development and mid-development testing. Member attrition and learning curves have been an issue during this build season due to the structure of the RoboUtes organization.

The RoboUtes team has engaged the community by promoting the excitement of space exploration and how science and engineering are dynamic and interesting fields. This is being achieved through an engaging social media experience and online presence. Through outreach, members of the public have been able to touch parts of the rover and talk to engineers about science and robotics, peaking their own understanding of the field. RoboUtes members are directly influencing members of the community through volunteer work, mentoring programs, and live hands-on demonstrations of the rover.

# ROVER SPECIFICATIONS

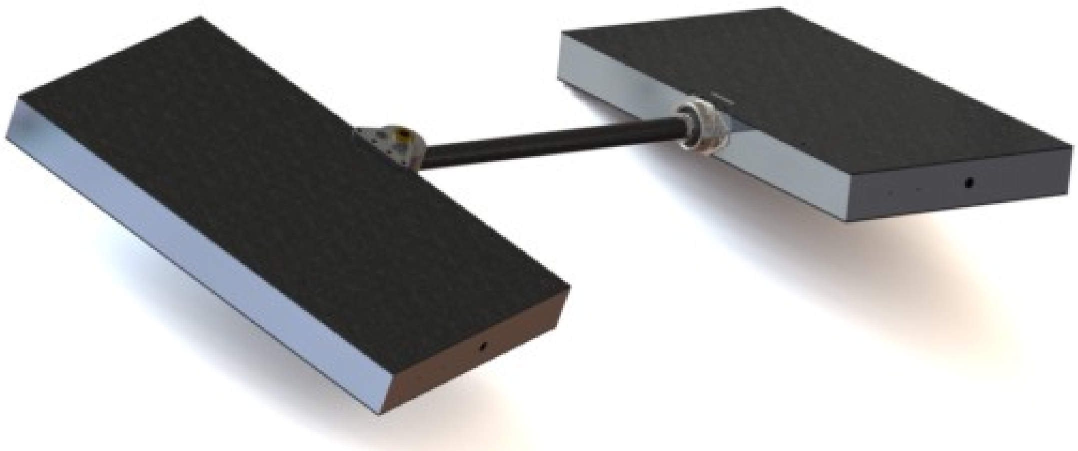
C.O.L.E. (Cellular Operated Land Explorer) is a dynamic mobile platform to facilitate sample collection on the Mars analogue field. The rover incorporates a distributed electronics and control system into a unique modern hardware body. The rover's systems are mainly composed of RoboUtes fabricated assemblies with limited commercial off the shelf development.

## HARDWARE

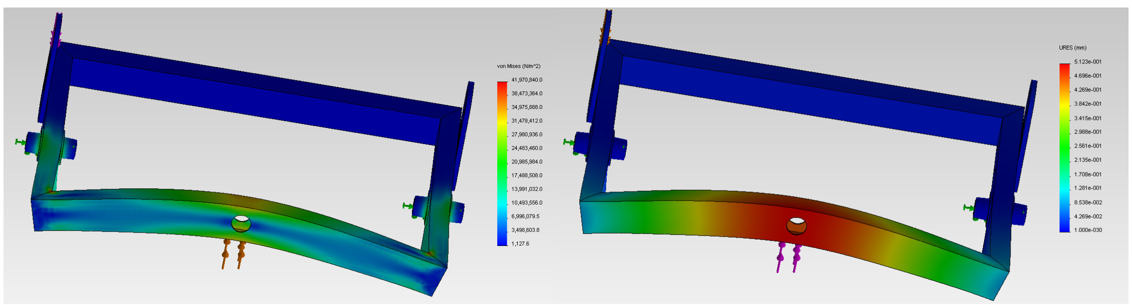
C.O.L.E.'s defining feature is its passive spine suspension system that gives it increased mobility on variable terrain. The rover is equipped with a strong lightweight four degree of freedom manipulator arm for sample collection. Various modular gripper designs have been evaluated for effectiveness yielding a strong final product. Multiple modular sample storage systems are also being evaluated for effectiveness of letting samples in but not out while the rover is experiencing steep slopes or dynamic loads.

### Chassis and Suspension

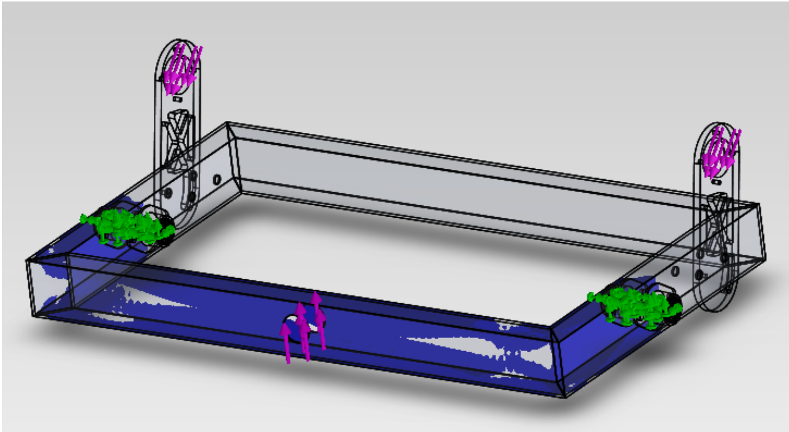
The rover chassis is split into forward and aft hubs connected by a two degree of freedom passive spine suspension system. The spine allows relative yaw and roll rotation between the two hubs giving the rover adaptability in various terrain types. The chassis hubs on the final design are comprised of 2" by 1" 6061 aluminum tubing with a 1/16" thickness. Each hub has an outer dimension of 12" by 21" with the tubes welded together. Composite decking material is used as top and bottom plate for each hub. The top decking provides a mounting surface for C.O.L.E.'s other systems and the bottom plate serves as a bash plate. Internal cross beams are welded to the aluminum to assist in load bearing on the decking.



The spine is comprised of a one inch diameter carbon fiber tube that passes through two bearings mounted on either side of the forward tube of the aft chassis hub. An insert in the forward end of the tube connects two plates on the forward hub and allows hub-relative yaw movement. This insert is built in such a way to facilitate the mounting of a yaw position sensor. The two chassis hubs and spine together weigh approximately five kilograms.




The RoboUtes did several stress and displacement analyses to determine the most appropriate chassis material. If the bearings are removed there is a large stress concentration at that point, also it was found that the maximum stress expected for each individual frame is about 30 Mpa during high dynamic loading which gives allows for a safety factor of two. Also in this analysis it was found that the corners experienced the highest stress thus the final design has L brackets at the corners to prevent collapse or bending. This would allow the rover to operate safely and without failing it its mission. This process allows for supports to be placed where the stress was highest to prevent failure. The displacement analysis gave insight as to how much deflection would result in the frame. Tools like Solidworks Simulation show where the majority of the stress occurs.



**Drive System**

The drive system is comprised of four independently driven wheels, each tied to a five hundred count rotary quadrature encoder. The wheels are sixteen inches in diameter allowing the rover to traverse large obstacles. The wheels are composed of five spoked polyurethane rims fitted with a pneumatic tire featuring an aggressive tread. Bearings couple the rim to an one half inch steel shaft.

In the prototype designs, the team used plates on either side of the wheel. It was found that the faces of the wheels are inconsistent and are not perpendicular to the direction of the output shaft. This defect lead to wobble in the wheels of the prototype chassis.

The final design uses the factory bearings to ensure square wheel mounting. The outside plate of the prototype design has been replaced with three tapped steel inserts to fit within the internal structure of the wheel. Inside plates are keyed into the half inch shaft and are rigidly connected to the wheel frame. Multiple inside plates are used to provide a stable keyed region and to space out the wheel from the sprocket. A machined eighteen tooth sprocket is fixed to the inside plating. The shaft then passes through two bearings mounted to either side of the aluminum chassis tubing into a collar to adapt it to a wheel position sensor. A plastic insert is placed in the chassis tube at the bearing location to prevent crushing.

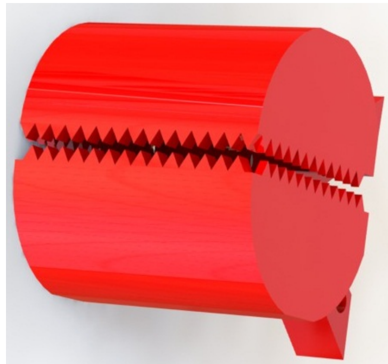

The wheel position sensor is currently a five hundred count rotary quadrature encoder and is protected inside the chassis. Shaft collars are placed on the outside of the wheel and directly inside the chassis between the bearing and the encoder collar. This ensures a secure back and forth movement of the shaft.

The wheel assembly is attached to its respective motor through standard bike roller chain on two sprockets. The motors are Anaheim Automation's BDPG-60-110-24V-3000-R47 DC permanent magnet motors. These motors use planetary gearboxes, run on 24 volts, and have a peak torque of 4166 oz-in. Their rated speed is 53 rpm and weight 1.75 kilograms each. With this rpm translated through the wheel the rover can travel at a calculated 220 feet per minute. Despite the weight, these motors allow the rover to travel at decent speeds and go up reasonable slopes and terrain. The motors are attached to the chassis using a quarter inch aluminum mounting plate. This plate attaches to the outside of the side chassis tube and is adjustable to allow for chain tensioning. Lightweight vacuum formed plastic guards encase the chain and sprocket system.

**Sample Collection**

One of the mission objectives that the rover has to perform is the collection of rock samples. Our arm is designed to have four degrees of freedom and a gripper system which are mounted on the front chassis hub of C.O.L.E. This allows our rover to have the dexterity and sample manipulation capabilities to reach hard to reach areas and to successfully complete our objective. The arm is also built structurally sound so that it can withstand the dynamic loading caused by the moving rover over complex terrain.

The arm is constructed from ¾" aluminum square tubing and is mounted on a geared turntable moved by a modified servo. The wrist joint is milled from PVC, and the shoulder and elbow joints are milled from aluminum. The shoulder joint is mounted directly to its gear motor. The elbow, wrist, and gripper are actuated via Bowden cables with the motors located on the front chassis. The elbow and wrist are connected using a pulley system while the gripper uses a pull cable fighting the torsion spring keeping the gripper closed. This system moves the majority of the weight off the arm and thus reduces the total torque needed by the motors and the dynamic loads experienced in the joints. To further reduce dynamic loads experienced by terrain traversal, the arm folds back into a stored configuration and the gripper latches onto a stable mount on the chassis. There is a potentiometer mounted directly to the elbow, shoulder and wrist joints to provide feedback to arm control.



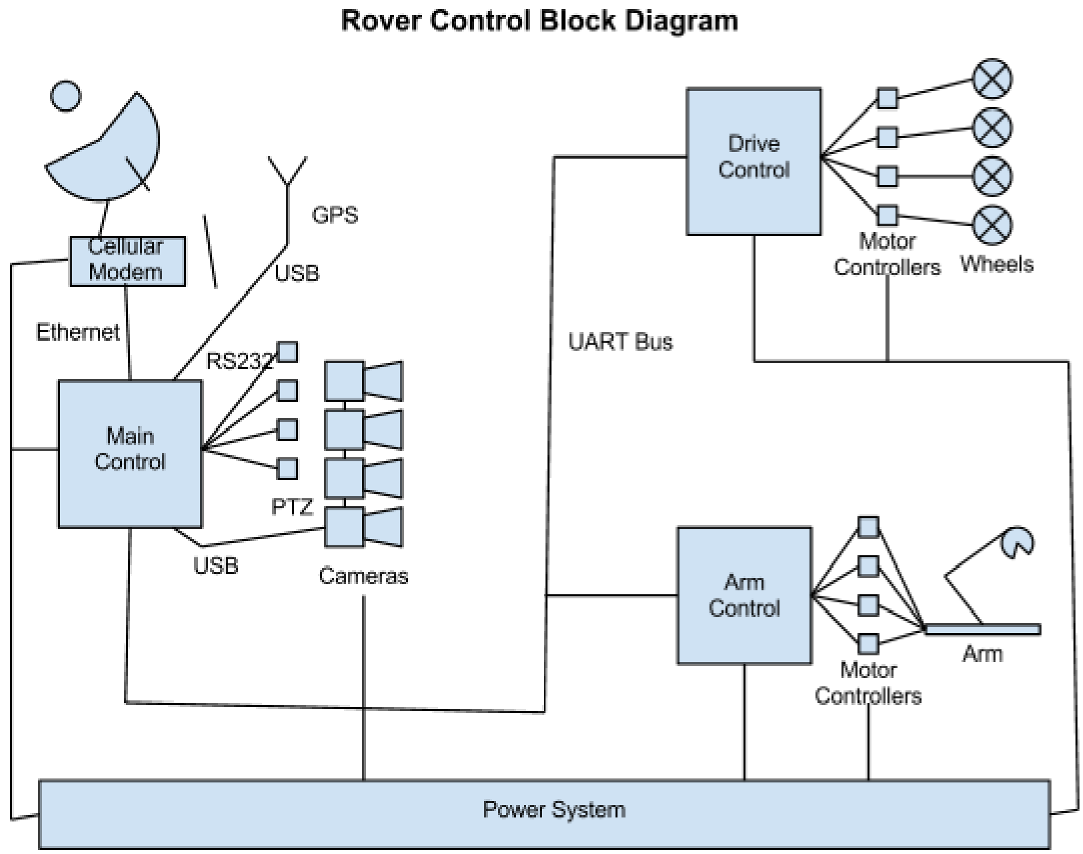
A wide variety of gripper designs moved into the proof of concept phase. These grippers were used during education and public outreach activities. By observing members of the community manipulate the various grippers, the final design was refined based off their feedback. The gripper system uses a two finger system with intermeshing gears and a four-bar linkage to collect the rock samples. The two fingers are shaped into two scoops to more efficiently collect rocks. The gripper opens using a motor and has a spring close system that reduces the complexity and the amount of sensors required by the gripper.

**Sample Storage**

A variety of designs for the rover's sample storage system have been considered, ranging from the most basic box to the overly complex. Functionality and weight were the top objectives for the sample storage system. The final design for the sample storage system is elegant, the bottom, sides, and top are formed from laser-cut plastic, chosen for their ease of manufacture, adequate strength, and low cost. They are chemically and mechanically joined to ensure strength and durability. Their assembly yields a sample storage area of 384 in^2, which seems more than adequate, given our projected number of sample acquisitions. The interior of the box is padded with low-density foam, to limit the potential for damage to either the sample box or the samples themselves when traversing uneven terrain.

Samples enter the box from above through a four inch square opening in the top of the box, large enough to accommodate any rock the rover may encounter during the event. The opening is surrounded by sloped deflection panels that help to direct the sample into the box, which reduces the amount of precision required to successfully transfer a sample from the gripper to the storage area. During normal operation, passage in and out of the sample storage box is blocked by two trap doors. These doors are mechanically limited such that they may only open downward, into the bay. The sample bay doors are in held in their closed position using a simple spring, whose strength has been matched to hold the doors closed only under unloaded conditions. Depositing a weight on the doors causes them to fall open, admitting the weight to the interior, and then spring back into a closed position to contain it. If for any reason the sample bay doors do not open sufficiently wide to admit the incoming sample, they can be manipulated with the gripper to achieve the desired result.

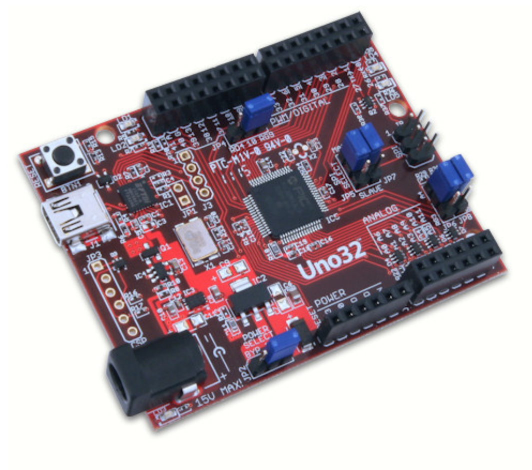
## ELECTRONICS




A highly modular system architecture was chosen for the electronic system of the rover. This enables multiple systems to be implemented by different teams on different platforms. This allows Computer Science students the ability to work in higher level languages that they are familiar with to implement things like user interface (UI) and network routing paths. Electrical and Computer Engineering students can work with small low power microcontrollers to implement high reliability, real-time control systems. Mechanical engineering students can use the simplified processing programming language implemented on Arduino compatible microcontroller platforms, allowing them to concentrate on the important mechanical aspects of systems.

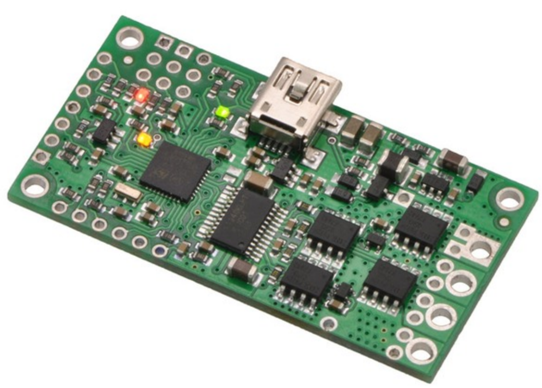
### Arm Control

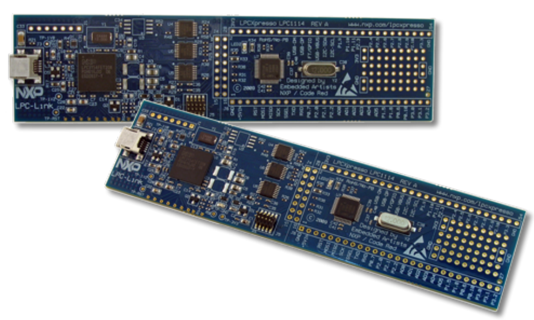
The arm's four degrees of freedom are controlled by custom designed, digitally controlled closed loop servo motors. The motors are controlled by a Digilent Uno32, featuring the PIC32, a 32 bit, 66 MHz MIPS based microcontroller. This control processor sends serial commands over a UART interface to four Pololu Simple Motor controllers, each includes a seven amp PWM motor controller and an STMicrodevices STM32 Cortex-M3 microcontroller. This controller ensures minimal motor stalls and maximizes motor and battery life.




**Drive Control**

The drive train control system is implemented using an Embedded Artists LPC Xpresso featuring the NXP LPC1114, a 48 MHz, 32 bit Arm Cortex-m0 microcontroller. This main controller interfaces with four, 500 count Quadrature Encoders (QE), and four Pololu 24v12 Simple Motor Controllers. The spine angle of the chassis is monitored using a 240 degree single turn 1K Ohm potentiometer (pot). With these controllers and sensors, independent controlled four wheel drive is implemented allowing the driver to change the major turning radius of the rover while it is stationary. This also allows a differential style drive allowing a zero meter turning radius.



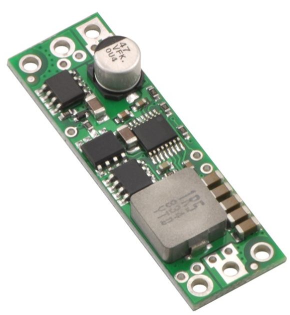
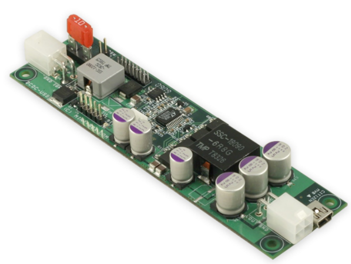


**Vision Systems**

The multiple cameras fitted to the rover allow for a variety of viewing angles. A boom mounted camera provides an overview of the rover and surrounding landscape. The boom is a rigid one-meter fixture which also houses the various RF antennas. The nose camera gives the driver a view of the front half of the chassis' orientation and direction. The gripper camera allows the arm operator to see the intended sample target and manipulate the gripper to its best position. The boom and nose cameras are Canon VC-C4R and VC-C4 models respectively. These cameras are capable of pan, tilt, and zoom (PTZ) motions, autofocus and autoiris features along with a 22x optical zoom thanks to the 4-64 mm lens. The gripper camera is a high definition webcam that is stationary in respect to the gripper to increase the operators accuracy while collecting samples. All the cameras can provide diagnostic information back to the users if needed along with their primary functions and are positioned to allow various views of the chassis and wheels to assist the driver. The cameras can provide various high resolution images but are set to provide a standard 640x480 image. Each camera can be put into a low power mode to conserve energy when not being broadcast back to mission control.


**Power Systems**

The power system consists of a lithium iron phosphate (LiFePO4) battery and adjustable buck/boost regulators for each voltage rail needed. The main motors require 24 volts thus the battery has been selected to provide 24 volts and be bucked down to the lower voltages. The battery chemistry was chosen due to its environmental benefit of lacking cobalt and the shelf stability of its energy density. This stability ensures more testing period cycles and overall use of each battery cell compared to other lithium batteries. The other big advantage is the relatively safer chemistry lowers the chance of fire during use and charging. The power regulators are comprised of two groups, the higher amperage 10 amp circuits that allow for programmatic voltages between 24 and 3.3 volts and lower amperage manually adjusted 3-7 amp modules. This allows quick reconfiguration of the voltage rails as needed when components are added or changed.

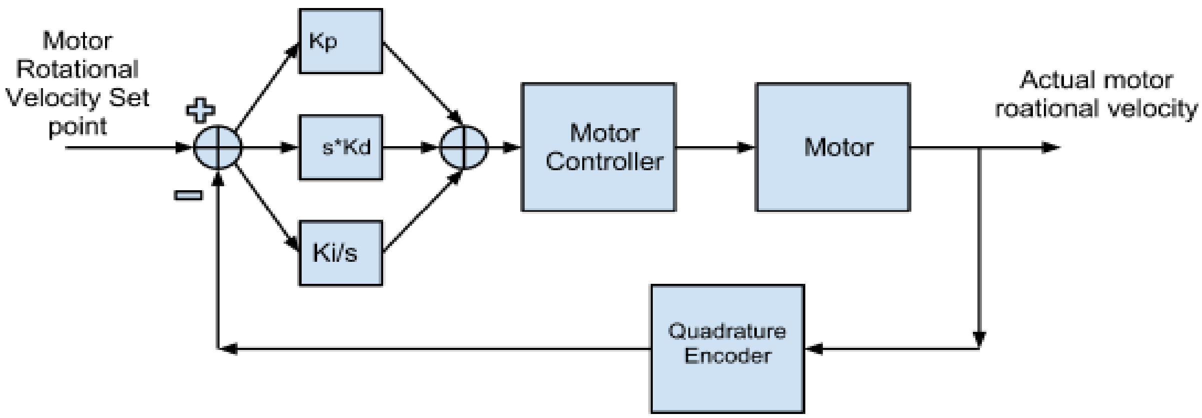
**Buggy System**

The RoboUtes have decided to add a daughter robot to scout for rock samples due to the limited time on the field the rover has during the competition. This “Buggy” will be deployed from the rover at the beginning of the competition time and scout ahead for rocks. The buggy uses a wifi connection to communicate its location and video back to the rover and finally through the uplink to the command center. The buggy is controlled by a separate human driver than the main rover and will provide sample collection support during the competition.

## SOFTWARE

### Drive System

The drive system implements several discrete time Proportional Integral Differential (PID) closed loop feedback systems. Individually tuned PID controllers manage the rotational velocity of each wheel using the QEs. The set points for the wheels are modified by the outer spine PID controller that has the desired spine angle as a set point and the actual spine position as the feedback element. This is then added to the desired forward or back velocity and given to the individual wheel controllers.




The motor velocity proportions are set so that the angle desired is achieved by spinning the motors proportionally towards each other to turn in the right or left direction. Thus if a left turn is desired, the left front wheel's RPMs are decreased or made negative while the back left is increased and vise versa for the right wheels. This change is applied using a PID controller to minimize the error between the set angle and the actual angle.

### Arm System

The control loop is closed with the three potentiometers on the shoulder, elbow and wrist joints of the arm. A limit switch is placed in the motor open spring closed gripper system to tell the controller that the gripper is in its maximum open state, turning off the gripper motor. This system implements individual joint control as well as reverse kinematic control, enabling the operator to control the arm naturally with minimal training and skill. This allows the drivers to concentrate on natural movement and not the complex control of four motors. The Uno32 was chosen because of its compatibility with the Arduino programming paradigm. This allowed speedy development of firmware.

### Vision System

Video is fed back up the uplink to the command center based on the bandwidth available. In a worst case scenario a single feed is provided and is switchable to each camera as needed by the operators. When bandwidth allows, rover nose, buggy, boom and gripper feeds will be selectable by the operator.

### Communications

Using a Cradlepoint access point and two Verizon LTE modems, internet access is provided for the main control system. Command data from Roboute mission control are received via UDP, demuxed, and distributed to the respective systems. Telemetry data is then sent along with compressed video back over the LTE data link and received at mission control.

### User Interface

The user screens used by team members at mission control serve various functions. The main screen shows the current location of the rover and the primary video feed. Secondary screens include the rover and buggy drivers interfaces, navigation and planning, and system status. The drivers use standard gaming controllers to facilitate the rover and buggy operation. Each command center member is responsible for a different task and has slightly different data available to them on their screens based off their role.

### Buggy Controls

The buggy is controlled by a wifi connection provided by the modem router and has a microcontroller programmed to interface with the drive motors. The buggy is also fitted with a fixed nose camera, this allows a second driver to be in control of the buggy independently from the mother rover.

## PRODUCTION AND TESTING

### RoboUtes Management Style

The RoboUtes Robo-Ops team is a student organization listed as a student club with the University of Utah. The club is extracurricular, interdisciplinary and is open for individuals of all skill levels. Because of the nature of the group member accountability and attrition has been a source of delay. Throughout the season there has been a smaller core group of members that put in the majority of the time with a larger group doing work when they are available. This season the build team has been predominantly mechanical engineering students with a few strong electrical and computer engineering students, with limited computer science support until midway through the build.

### Prototype Approach

The general approach to this year's build season was to take advantage of the strong interdisciplinary nature of the team members that expressed initial interest in the project. This would be accomplished by having the mechanical team focus on a single system at a time. When one system was completed the electrical team would take over that system while the mechanical members would shift focus to another subsystem. After electrical was finished the software team would move in with mechanical coming in to address issues and iterate the design after software was done. Some overlap would be needed and it meant that the electronics systems need to be modular but this approach looked the most promising. The chassis design submitted for the original proposal was meant to be a rapid prototype that would fix the major issues with last year's chassis and drive systems. Last year's software lead stated that theoretically last year's code should work on the new chassis, so we would start the first iteration with the new chassis, last year's electronics, and last year's code. This would give us at the minimum a driving rover platform that we could take to do outreach with. The hardware components were assembled relatively quickly in the season but unfortunately most of the software support for the project dissolved when classes began. On top of limited software support, last year's code documentation proved to be difficult to understand for new members. Last year's design also lacked the ability to get information back from the electronics components making troubleshooting difficult. This meant that the short term rapid prototype chassis was what was used for most of the build season for EPO activities. Only after new software support came to the club did we decide to abandon last year's PWM structure for a new serial structure. Then the team was able to proceed with the original iterative team approach.

**Campus Integration**

Students from all over campus were brought in to assist in all of the different facets of the Robo-Ops Competition. Business and marketing students joined the club to assist with the educational and public outreach areas of the team and a film major came to assist with our EPO video. The RoboUtes have sought more integration with students in other disciplines and this has brought dividends in increased interest in engineering and science programs.

## EDUCATION AND PUBLIC OUTREACH

Education and public outreach are very important for the RoboUtes. The major goal for the team was to increase interaction with members of the community. Though this a broader understanding of engineering was presented.

**Public Outreach**

The RoboUtes love presenting science, engineering, robotics, and space exploration to people that may not have much exposure to STEM subjects. Elementary age children have been very receptive to presentations due to their excitement when presented with a real life robot and a chance to interact with its makers. For example RoboUtes "inventors" members showed off C.O.L.E. to St Vincent de Paul's first grade class as part of their Invention Convention. The RoboUtes stressed the need to study hard and be creative when inventing.


The Leonardo Museum is a local science and engineering based museum that has asked the Roboutes to design and manage an outreach program at their downtown location for the general public. The Roboutes are currently organizing an off season event involving the local For Inspiration and Recognition of Science and Technology (FIRST) robotics teams and FIRST Lego League Teams that were mentored and/or coached by the Roboutes. The long term goal of the partnership is to introduce a "hacker/maker" space to the museum that would facilitate engineering workshops and day camps for the general public. This space would be staffed by RoboUtes volunteers and would provide a great avenue to introduce the fun and exciting concepts of engineering.

The RoboUtes presented at Mechanical Engineering Design Day at the University of Utah. Design day encompasses the culmination of the student engineering design projects that are worked on throughout the year. The RoboUtes both competed on design day with their personal robots as well as presented the mars rover and its functions to the audience.

During March 14th through the 17th the RoboUtes volunteered at the Utah Regional Championship FIRST Robotics Competition. We volunteered as Judges, Master of Ceremonies, Referees, and various other positions as well as set up our own booth to show off our rover and spark interest with the kids competing there and the audience.

The RoboUtes also volunteered at “meet an inventor” night at the University of Utah. Members talked with high school and middle school students about the rover, the club, the NASA competition and the benefits of engineering.

The team volunteered at the FIRST Lego League Utah Championship and multiple local qualifiers as master of ceremonies, judges, referees and other positions. RoboUtes also tabled a booth at these events, encouraging kids to try out the teams various gripper prototypes, explaining to children and adults the how various parts of the rover and arm worked, and generating an interest in science and engineering.

The RoboUtes are also volunteering at Bryce Canyon’s Astronomical Festival during May 17-20 that will coincide with the annular solar eclipse. By day, the half dozen RoboUtes on the “Away Team” will be helping with onsite activities, driving the rover and engaging with the community. By night the Away Team will be manning telescopes and assisting park rangers. At the same time the RoboUtes remaining at the University of Utah will be hosting a Mission Control Open House (MCOH, pronounced “emcoe”), where members of the public can visit mission control and get the opportunity to operate C.O.L.E. the RoboUtes rover. All RoboUtes, regardless of location will assist with solar viewing operations at both sites. These activities are in cooperation with the University of Utah Astronomy and Physics Department and the Clark Planetarium.

**Online Presence**

The RoboUtes had an increased online presence this build season. The primary focus was on social media with the most success being the RoboUtes Facebook page. Facebook allowed the team to provide up-to-date information to a large and diverse audience. The page achieved a maximum weekly readership of 4306 people. The RoboUtes have been “Liked” by 504 people, with the largest demographic being individuals between the ages of 18 and 24.

## Conclusion

The challenging experience of producing a Mars rover has been an exciting and fulfilling multidisciplinary experience for members of RoboUtes and students of the University of Utah. Through public presentations and other outreach, this experience has also benefited children and adults throughout the community.