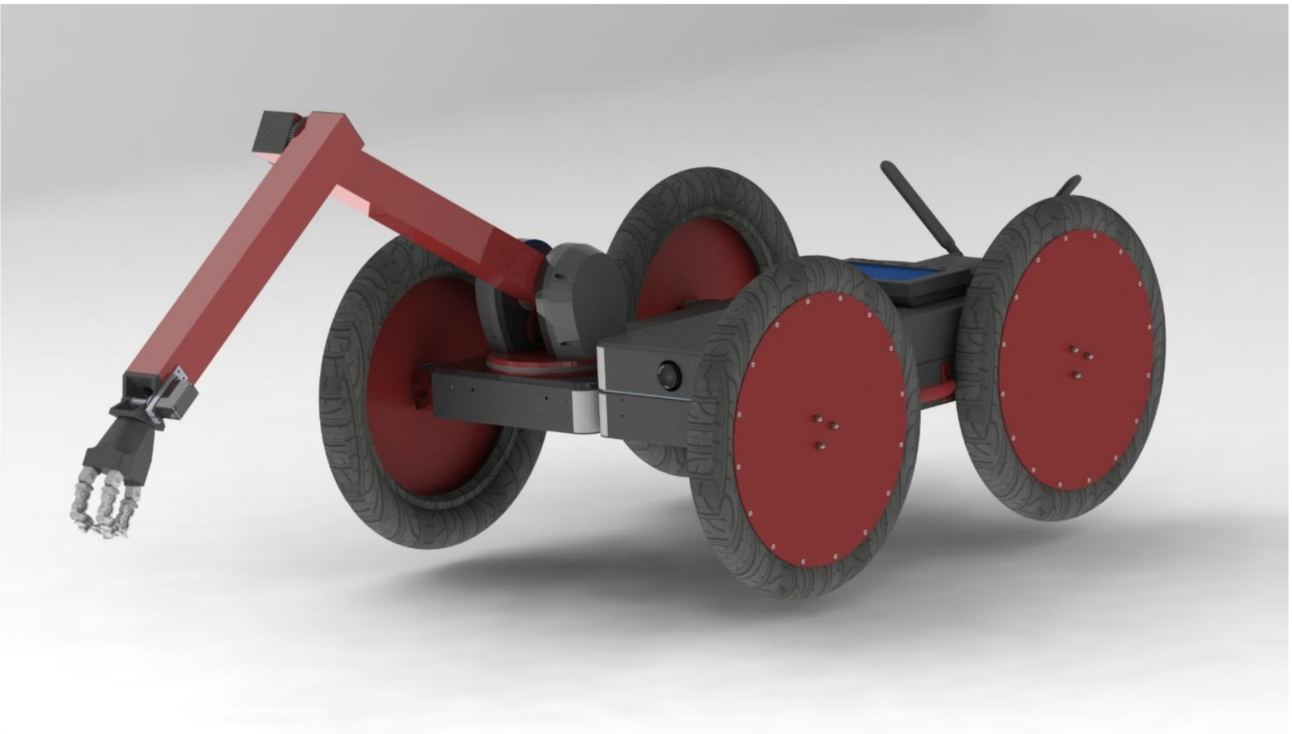

RoboUtes Final Technical Report for NASA RASC-AL Competition 2016

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Acronyms

API - Application Program Interface
FOV - Field Of View
FRMM - Field Replaceable Mobility Module
FEM - FRMM Electronics Module
COLE - Cellular Operated Land Explorer
CPT - Counts per Turn
CSAS - Compliant Spine Articulation System
DOF - Degree of Freedom
UAD - Universal Arm Drive
ROCS - Rover Onboard Computer Software
GUI - Graphical User Interface
FEA - Finite Element Analysis
EPO - Education and Public Outreach

Abstract.

The University of Utah Student Robotics Club (The RoboUtes) will compete in the 2016 RASC-AL Exploration Robo-Ops planetary rover competition. The RoboUtes will field a sophisticated teleoperated rover that has been specifically designed to complete competition tasks within the competition design constraints. Successful ideas from previous Robo-Ops entries have been incorporated into the new rover design, and new ideas and refinements have been applied to address previous shortcomings.

INTRODUCTION

The University of Utah RoboUtes have fielded a variant of the Cellular Operated Land Explorer (COLE) at all five previous RASC-AL Robo-Ops competitions. COLE VI was debuted at the 2015 competition and was a radical departure from prior versions. The system featured the first version of the Field Replaceable Mobility Modules, a rotary sample acquisition arm, and wireless communications between all major systems. In recognition of the success of the COLE VI platform, the RoboUtes have decided to take a more conservative approach to the design and development of the COLE VII platform. The team identified minor shortcomings in each of the subsystems and used an iterative approach to improve them.

SYSTEM DESCRIPTION

COLE is designed to traverse difficult terrain quickly and reliably while identifying and acquiring samples of interest. To accomplish these design goals COLE is outfitted with a highly capable mobility system, a versatile sample acquisition system, and an all-encompassing vision system. COLE is meant to operate in difficult terrain including dirt, sand, gravel, large rocks, and steep inclines. A description of the COLE VII major systems follows.

Chassis Design and Drive System

Chassis

The COLE VII chassis is divided into two rectangular halves joined by a compliant spine. Each half of the chassis is composed of a base structural section with a hinged lid. The lid is held closed by quick release clasps to allow easy access to the internal components. The FRMMs have been moved to the inside of the chassis rather than the low slung pods of COLE VI such that the bottom of the chassis can remain entirely flat. Eliminating protrusions from the bottom of the chassis improves COLE’s obstacle traversal capability by decreasing the chance that COLE will get hung up on obstacles. The side by side chassis arrangement pioneered on COLE VI has been retained due to the improved approach and departure angles afforded by the design. The overall dimensions were again selected to maximize the wheelbase while remaining narrow enough to easily pass through standard doorways. Due to the modular nature of the design, the entire chassis can be swapped out if necessary to adapt the robot to new environments.

CSAS

The Compliant Spine Articulation System, a passive roll joint between the two chassis halves, has been retained. The CSAS allows COLE to traverse large obstacles while maintaining 4-wheel contact with the ground, making it extremely capable on rough terrain without the added cost or complexity of a rocker-bogie or walking beam style suspension. The primary CSAS rotating element is an igus(™) slewing ring featuring integrated engineering plastic bearing surfaces. The slewing ring is constructed from aluminum and glass filled plastic, resulting in a lightweight roll joint with load ratings exceeding the anticipated loading conditions.

Mobility System

Following in the wheel-paths of previous COLE robots, COLE VI features the four-wheel drive slip-steer mobility platform. The robot is capable of approximately 1.73 meters per second flat ground traversal. Each of the four wheels is 406 mm in diameter. The Field Replaceable Mobility Modules were significantly redesigned to improve performance and manufacturability.

FRMM

COLE VII uses interchangeable drive modules similar to the system developed for the previous COLE platform. As in the previous implementation, all four modules are interchangeable and easily removable. Each Field Replaceable Mobility Module (FRMM) contains a single 24V Maxon gearmotor producing 9.3 Nm of continuous torque at 4.2 A. A motor-mounted 10 CPR shaft encoder provides an output resolution of 1030 CPR after the 103:1 gearbox. Running at rated voltage, the maximum traverse speed is 1.73 m/s. Throttle control is adjustable down to 1 mm/s linear speed for fine motor control during rock climbing events.

The COLE VII FRMM replaces the carbon fiber, printed plastic and heavy aluminum plate from the previous FRMM with a 0.063” thick square aluminum tube, resulting in a smaller, lighter, more robust, and more readily manufactured drive module. The wheel is supported with a spindle and bearing similar to many automobiles, providing a significant weight and performance advantage over the slewing bearing design previously used. The new FRMM slides into the chassis from the side and is quickly secured with two fasteners. The retaining bolts are easily accessible from the outer face of the module (through a skeletonized section of the wheel), unlike the previous design which required bolts to be dropped through the chassis from the top.

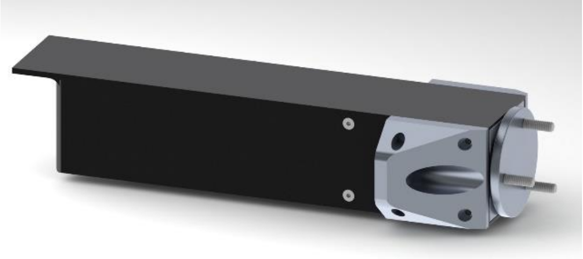

Figure 1 - The revised Field Replaceable Mobility Module

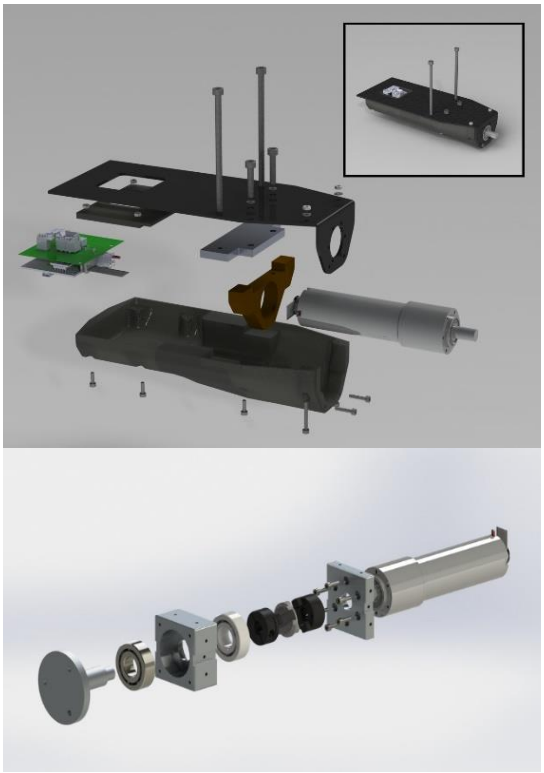

Figure 2 - A comparison of the old FRMM (top) and the new revision.

The electronics are no longer located in the FRMM (as they were on the last COLE rover) as they are considered extremely reliable. This simplifies the assembly and results in a more convenient form factor, allowing the modules to fit within the chassis. The premise of the FRMM Electronics Module (FEM) has been retained from the previous design, integrating a drive electronics on a single custom PCB. The FEM consists of a Teensy 3.1 microcontroller, motor controller, nRF radio, and current sensor. Due to this modular design each FEM is capable of closed loop control on a variety of motors whether attached to COLE, mounted to a tabletop with a power supply, or attached directly to a battery for independent use. In the event of sensor failure, closed loop control can be abandoned and replaced with feed forward commands.

Manipulator Arm

A teleoperated robot must be capable of interacting with its environment if it is to accomplish any science tasks. The purpose of the Robo-Ops competition is to collect various rock samples, and previous competitions have demonstrated that a relatively simple manipulator can collect rocks and compete effectively. Modern planetary science has moved beyond the mission objective of “collect rocks” however, and as such the RoboUtes elect to field manipulator arms capable of completing more advanced tasks.

The COLE VII manipulator is effectively a 3-DOF serial manipulator followed by a 1-DOF wrist for end effector orientation. With a maximum reach of approximately 0.75 meters the arm has an operating area of about 1.5 m^2. This workspace is mapped in Cartesian three-space, with the origin 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 a combination of the shoulder, elbow, and wrist joints. Using this convention, the arm can be easily positioned at any point in the operating area using a simple ordered triple of coordinates, i.e. P = (x,y,z).

The structural elements of the manipulator are machined from 2” square aluminum tube for light weight and high strength. Rotating joints are constructed using a combination of Igus IGlide slewing rings and rolling-element bearings. 3D printed components are used for dust covers and safety shields around exposed gears and other moving components.

Shoulder

The rotary shoulder joint used in the previous COLE arm has been revised, supporting the forearm link on both sides with slewing bearings. This design is stronger and significantly stiffens the manipulator, but adds to the weight of the assembly.

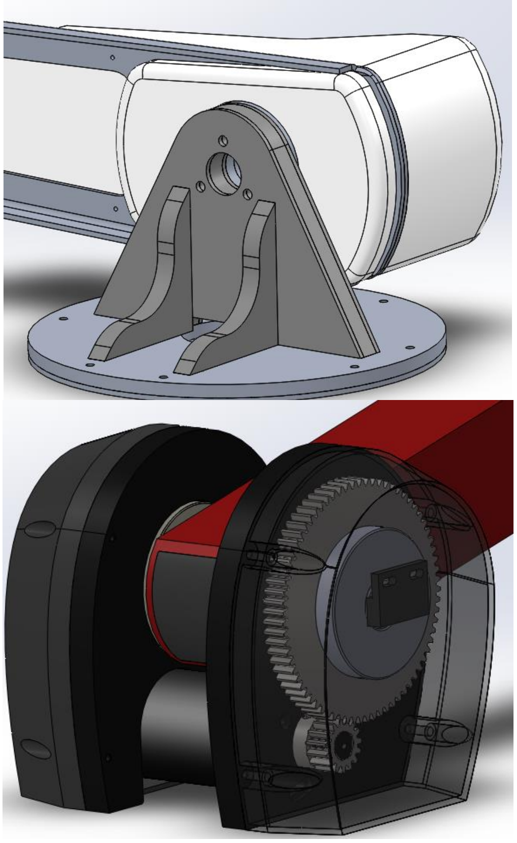

Figure 3 - A comparison of the old shoulder joint (top) vs the new, revised version.

The shoulder actuators have been completely replaced, with a single Maxon brushless motor replacing the two Pololu actuators from the previous arm. The Pololu motor pair was somewhat underpowered, and experienced an alarmingly high rate of failure. The single Maxon motor develops more than five times the torque of the previous motor pair, dramatically improving the payload capacity of the COLE VII arm. This additional power allows the manipulator to maintain an arbitrary position in the workspace, while the previous shoulder motors would begin to overheat in some positions. While high torque is necessary to reach some positions, the arm is powerful enough to seriously damage itself in a collision with the workspace. An adjustable friction clutch built into the shoulder joint allows the peak transmitted torque to be adjusted based on the system’s expected payload.

Friction Clutch

Due to the difficulty of teleoperation in an unstructured environment, the manipulator must be able to withstand repeated collisions with obstacles. An adjustable slipper clutch provides mechanical torque limiting at the shoulder joint, protecting the manipulator in the event of a collision and allowing operation to resume as soon as the over-torque condition is removed.

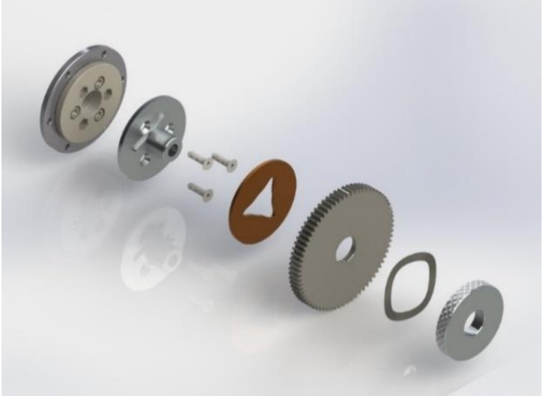

Figure 4 - Exploded view of the COLE VII slipper clutch assembly.

The slipper clutch is simple to manufacture and relatively lightweight compared to other non-destructive torque limiters (magnetic or fluid couplings, ball-detent torque limiters, etc.), and has obvious advantages to sacrificial devices such as shear pins. In this implementation, a woven brass friction element engages the face of a steel gear with force applied by a wave spring. Tightening the knurled nut increased the friction between the gear and friction material, increasing the torque that can be transmitted to the shoulder joint of the manipulator.

<u>Wrist</u>

The continuum wrist of the previous two COLE iterations has been abandoned in favor of a simple servo actuated pitch DOF only wrist. While the continuum wrist was very capable, the RoboUtes found that the operator never used the yaw DOF. The system was quite heavy, requiring six linear actuators. The new Servo Actuated Wrist (SAW) only requires a single servo to operate making it simple and lightweight. The SAW is capable of approximately ±70 degrees in pitch from the neutral position. The primary purpose of the SAW is to keep the end effector normal to COLE's horizontal plane.

<u>Gripper</u>

COLE's gripping system continues to be the subject of intense study, design, and revision. Design of a bio-inspired compliant finger has been the subject of an independent study by David Van Ness. The goals of this design include decreasing finger compliance to limit unwanted deflection, decreasing finger cross section to improve reach into small spaces, and bidirectional actuation to permit gross manipulation of non-target objects.

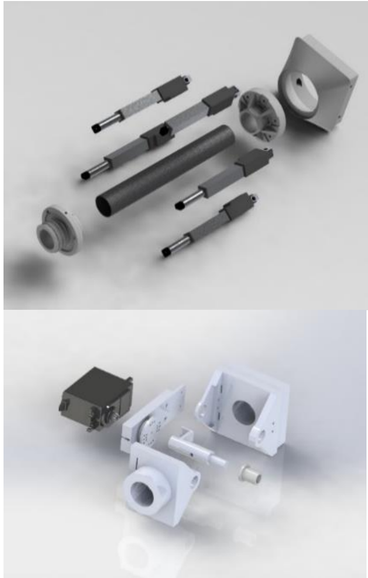

Figure 5 - A comparison of the previous continuum wrist (left) with the new pitch DOF only wrist

The finger joints are comprised of a bio-inspired bearing surface between bones, compliant collateral ligaments to limit unwanted sideways deflection and maintain joint positioning, and compliant volar ligaments to limit finger extension. The goal of these elements is to allow just enough compliance to protect the finger from damage while also limiting unactuated motion of the joints to permit the fingers to enter small cluttered spaces precisely.

The fingers are located on a 3D printed plastic common palm in a 1-2 arrangement in order to accommodate target rocks of various sizes. Finger flexion is achieved by a single linear actuator pulling on tendons routed from each finger through the palm and wrist to a load balancer. Finger extension is accomplished in the same way via a separate set of tendons. This actuation method decreases the number of required linear actuators from three to two resulting in a decrease in weight and increase in reliability. See Figure 6.

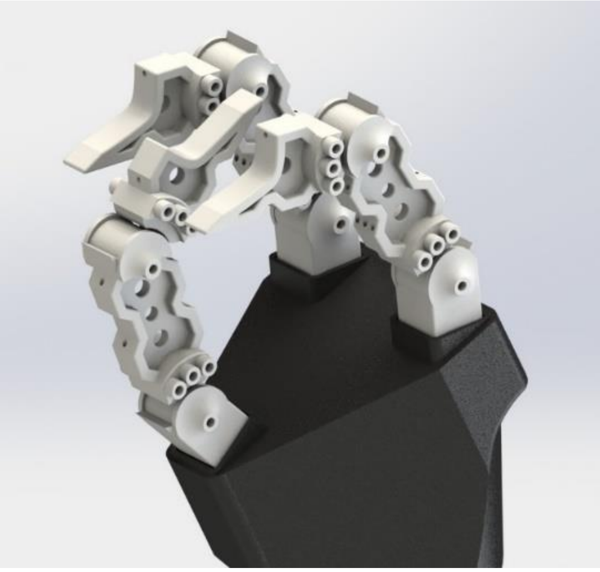

Figure 6 - The COLE VII end effector

Vision System

COLE VII builds on the very successful vision system of the last COLE rover, again implementing the Axis Communications F44 platform. The F44 main unit supports high definition video streaming of 4 cameras on the robot and locally encodes the video before transmitting it to a known IP address. Axis provides an API through which mission control can initiate feeds and set streaming parameters. Several 1080p sensors are available for the F44 unit, and COLE VII has two cameras with 113 degree FOV and two with 194 degree FOV. The F44 system can be seen in Figure 7.

Figure 7 - Axis F44 camera system

<u>Drive Cameras</u>

Wide angle cameras are positioned on the front and rear of the chassis on opposite chassis halves. Due to the mirrored nature of this arrangement, it is equally comfortable for the drive operator to travel forward or in reverse.

<u>Arm Cameras</u>
The arm features two cameras for aiding in sample acquisition. A workspace camera is mounted to the forearm, oriented to provide view of the hand when the hand is in a typical sample acquisition position. This camera helps the user to align the arm along the longitudinal plane of the sample using the turntable, and lower the hand within a few inches of the sample, using the shoulder joint. At this point the user switches to a camera embedded in the palm. This camera allows the user to align the arm with the latitudinal plane of the sample. Once the sample is aligned, the user must simply make minor adjustments to keep the sample centered in the palm camera as the arm is lowered to make the grab. When the sample fills the field of view in the palm cam, and seems adequately caged in the workspace cam, the user may close the hand and try for a grab.

Power System

The power system on COLE VII allows for numerous battery configurations. Virtually any battery chemistry can be used, and the power system is rated for input voltages up to 35V. For the competition a nominal 22.2V, 6Ah Lithium Polymer battery will be used allowing for 2.4 hours of run time and providing the appropriate voltage to the mobility system.

Control and Communications System

Rover Onboard Computer Software

COLE VI uses Intel's latest generation NUC platform to handle all of its highest-level computing operations. The NUC platform provides extremely low power consumption (15 W typical) while still being able to handle relatively heavy computing loads and taking up minimal physical space. See Figure 8 for an image of the Intel NUC.

Figure 8 - Intel NUC used as Rover Onboard Computer

Network Architecture

COLE VII uses a tiered communications framework that splits the burden of delivering data from mission control the relevant systems aboard the rover into manageable, debuggable, sub-systems. All of the communications libraries mentioned below were written in-house (See Figure 9 for the communication flow chart). The first of these systems, called Iris, is responsible for managing all internet-traversing data except video. Iris is a highly-abstracted socket interface that manages everything from handling multiple client connections to dealing with connectivity failures that may occur during the competition. Iris will alert users to the current state of the network, but will require no human-intervention to repair network issues. All of COLE's internet-bound data uses an unthrottled connection on T-Mobile's 4G LTE network.

Once Iris has delivered data from mission control to COLE, any data needed only by the Rover Onboard Computer Software (ROCS), will have reached its terminus. For data that needs to reach lower-level systems onboard the robot, serial connections and a serial-library called Hermes will be used. Hermes allows for efficient packaging and delivery of data between systems over a serial connection. The Hermes protocol is used between ROCS and the Arm/Drive Masters, the Lidar Controller, and Power Distribution microcontrollers. After reaching an embedded system using Hermes some data will need to reach several "slave" systems which directly control the actuators.

Routing serial lines to all of these very low-level systems involves far too much overhead in terms of both hardware capabilities and more tangible things like cable routing. To solve this issue COLE VI uses nRF24l01+ radios to communicate wirelessly with all of the lowest-level onboard systems through a library called Hydra. Hydra performs basic stringstream based communication with the embedded controllers, and handles acknowledgements, negative acknowledgments, and retransmits as required to ensure steady wireless data flow.

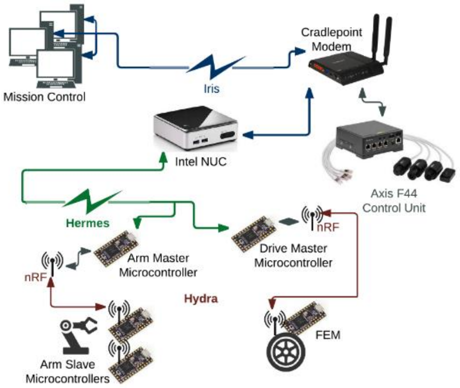

Figure 9 - Flow of data and commands from mission control to the various robot subsystems

Primary Modem

COLE's connectivity device is a CradlePoint IBR650 Integrated Broadband Router, donated by CradlePoint. This is a ruggedized mobile internet solution designed to provide high-speed internet on 12V DC power in dirty, hazardous conditions. The router features 2 large paddle-style antennas, each capable of approximately 2 DBi of gain. The router has proven capable of holding a fast connection even in the RoboUtes Lab, a concrete room located underneath the stately Kennecott Engineering Building.

Mission Control GUIs

Controlling a complicated system like COLE VII is best handled by multiple operators at multiple computer terminals. Consequently, the Mission Control software has been broken into different terminals, with each terminal corresponding to a specific and manageable task. These terminals were written in-house in C# and distributed to the various computers in Mission Control as standalone executable files for convenience. The terminals are:

Engineering - the Engineering Terminal is designed to provide the operator with all of the data necessary to monitor the current health of the robot. As a result, this terminal will receive more types of data than any of the others. Everything from telemetry to electrical current to speed will be accessible to the engineer. The engineer will also be able to interact with some of these systems by instructing them to do things like ignore data from broken potentiometers, or even cut power to a system altogether.

Drive & Arm - the Drive and Arm Terminals deliver their users all of the necessary data to control their namesakes through a joystick. Each of these terminals deliver relevant state information to the user that will be used to make informed commands. Both of these operators will use additional information from the logistics and engineering terminals as needed.

TESTING STRATEGY

Mathematical and Software Simulation

Regular meetings are held at the RoboUtes lab in order to brainstorm potential robot ideas. Elementary laws of mechanics, dynamics, or electronics are implemented at this stage to determine if an idea is feasible and worth pursuing. Ideas that pass this stage will be modeled and simulated using design software. If it is a mechanical part, it will be built in Solidworks and may be subject to FEA or motion study analysis. If it is a computer program, it may be subject to a bandwidth test. These tests ensure a rigorous study of the robot's proposed systems and ensure the viability of the designs before manufacturing begins.

Proof of Concept

Once initial designs are completed, the RoboUtes will typically manufacture a proof of concept prototype. This prototype is an approximation of the design, and highlights the key areas of concern. Simplifying the construction allows for the prototypes to be built quickly and cheaply while still allowing mechanism or system performance to be analyzed. This in turn allows for rapid iterations of designs.

Prototype Testing

One a system has been fully developed the prototype is generally "bench tested," that is, tested in isolation from other components. This stage ensures that the prototype works as designed and allows for debugging in a controlled environment. Components may cycle through this stage many times, being designed and redesigned iteratively until the optimum solution is found.

Integration Testing

Once a component has been shown to work well in an isolated environment, it is integrated into COLE for a full system test. This is often where the most complicated problems are found. Interactions between different systems create unexpected bugs, which require time and attention to solve. As a result, this stage of testing is especially important, as all of the systems must work with each other in order for the robot to perform well during competition.

Testing Results

Attending a large number of EPO activities has the added benefit of rigorously testing our drive system. Allowing unexperienced operators to handle the robot exposes design flaws that would otherwise remain hidden. These flaws could later manifest themselves during the competition. Since COLE VII will be using the same wheels and drive motors as last year, at full power COLE will climb almost any obstacle including rocks bigger than its tires and inclines greater than 45 degrees. The rover will attempt to climb walls, usually flipping itself in the process. In addition, the arm construction is considerably stiffer than last year, and with the turntable drive motor producing significantly more torque. These changes further improve the performance of the arm.

COMPETITION STRATEGY

Overall Philosophy

The RoboUtes have observed that the most successful teams at Robo-Ops field highly mobile rovers which are able to rapidly cover most of the Rock Yard. With this in mind, the RoboUtes have constructed a robot with an emphasis on terrain traversal, capable of traveling quickly to any area of the rock yard and successfully negotiating even the most difficult obstacles. Covering the course quickly allows operators more time to identify and retrieve rock samples.

The Game Plan

The RoboUtes' previous rover heavily emphasized lightweight, modular components. This year's revision of the COLE platform retains those emphases, although the manipulator system features significantly more robust components at the cost of somewhat increased weight. Although some increase in weight was necessary to guarantee rover performance, the RoboUtes still hope to be light enough to compete in one of the later time slots. Many objects of interest will already be located in the competition course from watching the feeds of previous rovers. These objects will be mapped on the same map the logistics operators use to add objects found during the RoboUtes competition run.

Starting from the top of Mt. Cosmos, COLE VII will rapidly traverse to the Lunar Craters. Approximately 10 minutes will be spent travelling to and gathering samples from the craters. Operations will cease for a period of 5 seconds when passing the Buffalo Memorial Crater, as COLE pays its respects to departed friends. The goal for this portion of the course is to collect as many samples as possible in a short period of time, and move on to areas with higher value targets. The rover will then explore the base of Mt. Cosmos for targets while travelling towards the Mars Yard. The time allocated to this phase of course exploration is 10 minutes. Next, the robot will move into the outer edge of the Mars Yard and attempt to collect a few high value samples. COLE will not proceed further into the boulder field unless an alien life form is located, and collection is deemed reasonably safe. The plan is to spend 15 minutes collecting samples from these two areas and return to the starting point with a 5-minute safety buffer.

When a rock sample is discovered, the pilot will use graphic overlays on the primary drive camera to position the rover so the target is centered in the workspace of the manipulator. The arm will be deployed and acquisition will be attempted. It is the discretion of the Mission Commander to terminate an acquisition attempt if recovery is determined to be unlikely. Upon this determination, COLE will move on with the planned itinerary until another sample is encountered.

BUDGET

As mentioned in previous communication, the RoboUtes laboratory experienced a battery fire early in Fall 2015. Most robot components and tools were destroyed by fire or water damage, and had to be replaced. University insurance was able to cover some, but not all of the damaged hardware. Due to decreased membership and the time required to repair the lab, the RoboUtes were not able to fundraise as effectively as in past years. In addition to the stipend provided by RASC-AL, RoboUtes received in-kind donations from Maxon Motor and Igus totaling ~$1500. The RASC-AL stipend was used to purchase all components and tools not donated by the above.

The final value of the robot components is approximately $9000, about half of which was donated or replaced using insurance money. Other project expenses include ~$4700 for registration and travel to the competition. A final budget report will be compiled following the competition.

PUBLIC OUTREACH

The RoboUtes place a heavy emphasis on public outreach and education. The team holds frequent events that are attended by students of elementary and secondary school age. The students are given the opportunity to operate current COLE robot platforms in the hope of inspiring the students to pursue education in science, technology, engineering, and mathematics.

Education and public outreach events have also included tabling at fairs and events, attending College of Engineering events, hosting robotics events, and visiting schools. These opportunities allow the RoboUtes to engage a diverse audience. RoboUtes help host a Girl Scouts “Robots Rock” event twice per year. The scouts are able to drive COLE, manipulate the sample acquisition system, and talk to the team about science and engineering.

Physical Dimensions

Mass	30	kg
Length	100	cm
Width	73	cm
Wheelbase	50	cm
Height	45	cm
Wheel Diameter	41	cm

Drive

Rated Payload	40+	kg
Max Speed	1.73	m/s
Obstacle Size	0.25	m

Arm

Degrees of Freedom	4	
Reach	0.75	m
Operating Area	1.6	m^2
Rated Payload	1	kg
Grip Strength	45	N

Power

Chemistry	Lithium Polymer	
Battery Voltage	24	V
Battery Rating	20	Amp Hour
Minimum Operating Time	2.4	Hours
Typical Operating Time	4+	Hours
Voltages	5	V
	12	V

Rover's Onboard Computer

Processor	Intel i5-5250U	
Cores/Threads	4c/8t	
CPU Speed	1.6-2.7	GHz
RAM	8	GB
GPU	Intel HD Graphics 6000	
Power	15	W

Communication

Modem	Cradlepoint IBR650	
Max Up	50	Mb/s
Max Down	100	Mb/s
Network	T-Mobile 4G LTE	
Reported Up	4	Mb/s
Reported Down	12	Mb/s
Reported Latency	180	ms

Teensy 3.2

Processor	Cortex M4	
CPU Speed	96	MHz
RAM	64	kb
ADC	16	bit

Pololu Dual Motor Driver VNH3SP30

Input Voltage	5-16	V
Continuous Current	9	A
Peak Current	30	A
PWM Frequncy	10	kHz

Pololu Simple Motor Controller

Input Voltage	5-40	V
Continuous Current	12	A
Peak Current	30	A
PWM Frequency	21.77	kHz

Drive Motors

Maxon B72EEFDD9B01		
Input Voltage	24	V
Rated Current	2.2	A
Stall Current	5	A
Rated Torque	10.21	Nm
Stall Torque	29	Nm
Rated Speed	80	RPM