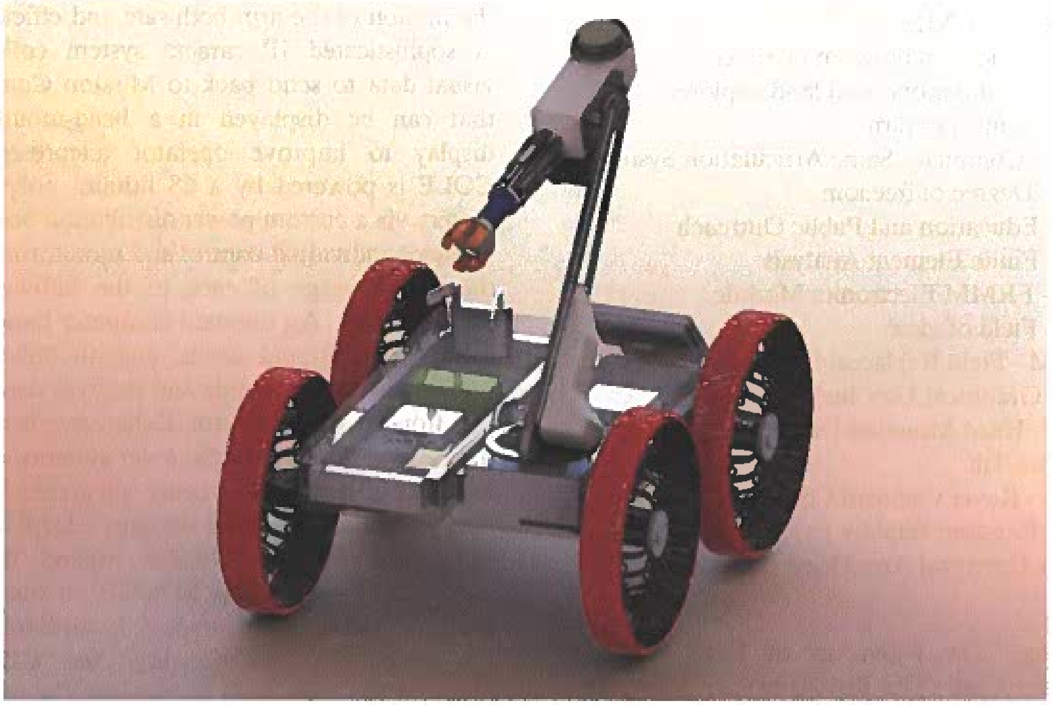

# ROBOUTES FINAL TECHNICAL REPORT FOR NASA/NIA RASC-AL COMPETITION 2015

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## ACRONYMS

API - application program interface
COLE - cellular operated land explorer
CPT - counts per turn
CSAS - Compliant Spine Articulation System
DOF - Degree of freedom
EPO - Education and Public Outreach
FEA - Finite Element Analysis
FEM - FRMM Electronics Module
FOV - Field of view
FRMM - Field Replaceable Mobility Module
GUI - Graphical User Interface
HMD - Head Mounted Display
PT - Pan Tilt
ROCS - Rover Onboard Computer Software
RRT - Random Rapidly Expanding Trees
UAD - Universal Arm Drive

Abstract. The University of Utah Student Robotics Club (The RoboUtes) will compete in the 2015 RASC-AL Exploration Robo-Ops planetary rover competition. The RoboUtes have designed, fabricated, and programmed a telepresent sample collection rover named COLE VI, the Cellular-Operated Land Explorer. COLE will be sent to NASA's Johnson Space Center in Houston Texas for the competition. The telepresent robotic system will be controlled from Mission Control in the University of Utah's Kennecott Engineering Building via a mobile broadband connection. COLE utilizes a dual-platform chassis which allows the left and right chassis halves to pitch independently to traverse rough terrain. The chassis rolls on innovative carbon fiber wheels that provide locomotion as well as shock absorption and vibration attenuation. Each wheel is driven by a Field Replaceable Mobility Module which performs closed-loop control on velocity and position for precision driving in unstructured environments. COLE's manipulator arm utilizes a similarly modular servo drive called a Universal Arm Drive to articulate the arm and retrieve samples. Advanced motion planning techniques are employed to make the motion of the arm both safe and efficient. A sophisticated IP camera system collects visual data to send back to Mission Control that can be displayed in a head-mounted display to improve operator telepresence. COLE is powered by a 6S lithium polymer battery via a custom power distribution board, allowing individual control and monitoring of the power usage of each of the individual robot systems. An onboard computer handles local computational needs, and an onboard broadband modem sends and receives data to and from Mission Control. Exhaustive testing has been performed on the rover systems, and test data is continually being integrated into new and improved rover designs. COLE was developed using a $10,000 stipend from NASA/NIA, as well as $17,000+ of outside financial and material support. In addition to its competition functionality, the COLE platform has been used to promote the study of science, technology, engineering, and mathematics in both the local community and online, and is frequently used as an outreach tool at educational events. The development of COLE VI has been of incredible educational value to the students in the club and the local community, and is on track to perform admirably at the 2015 Robo-Ops Forum in June.

## INTRODUCTION

A variant of the Cellular Operated Land Explorer (COLE) has competed at all four of the previous Robo-Ops competitions. COLE is the RoboUtes' signature mobile robotics platform, and work is ongoing to optimize and refine the system to be more capable, reliable, and efficient. Robo-Ops 2015 will be the debut of COLE VI, the most radical redesign of the platform to date. The mobility platform, sample acquisition arm, and wireless communications systems have all undergone extensive review and redesign. Aggressive pursuit of corporate sponsorship have allowed for the inclusion of components and systems previously considered to be far out of reach. Small interdisciplinary teams including a mixture of mechanical, electrical, and computer engineering students have been working diligently on each subsystem, developing mechanical, electro-mechanical, and software elements in parallel to ensure easy and effective compatibility. Subsystems that in previous years were written off as "minor details" like power distribution, cable management, and heat management system have been given considerable attention to ensure that they will be just as well-engineered and reliable as the mobility, vision and sample acquisition systems.

# SYSTEM DESCRIPTION

COLE is designed to be a highly capable off-road exploration vehicle. Durability, speed, and precision are the primary objectives of the mobility system. This is a system designed to explore an entire planet (consisting of a hill, a sand pit, a rock yard, and a crater surface) in an hour, and leave no brightly-colored stone uncollected. A description of COLE VI's main systems follows. See Appendix 1: Technical Specifications for a quick-reference list of COLE's vital statistics.

## CHASSIS AND DRIVE SYSTEM

### CHASSIS

The COLE VI chassis consists of two rectangular frames made of 6063 aluminum box tube, joined together into a single chassis unit by a compliant spine (see below). The underside of the frame is protected by a composite layup of carbon fiber and spectra for impact and abrasion resistance, respectively. The upper enclosure is made up of lightweight mylar sheeting, as ingress protection is the main objective, rather than collision protection. The major robot components (drive modules, manipulator arm, computer, battery, modem, etc.) attach to the chassis using quick-release fastening approaches (quarter-turn latches, Velcro, etc.) such that systems can be reconfigured or serviced at a moment's notice. The chassis dimensions were selected to maximize COLE's wheelbase, but also allow for safe passage through doorways. The extremely modular nature of the chassis and rover platform in general will allow for future adjustment of chassis sizing for the best terrain traversal results.

### COMPLIANT SPINE ARTICULATION SYSTEM (CSAS)

COLE VI features a passive roll joint between the two chassis, referred to as Compliant Spine Articulation System. 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 light weight roll joint with load ratings exceeding the anticipated loading conditions. The major difference between the previous COLE CSAS and system used in COLE VI is the 90 degree rotation of axis of compliance, resulting in left and right chassis halves instead of the previous fore and aft chassis halves.

### MOBILITY SYSTEM

Following in the wheel-paths of previous COLE robots, COLE VI features the four wheel drive slip-steer mobility platform. As noted in the technical specifications, the robot is capable of approximately 1.73 meters per second flat ground traversal. Each of the four wheels is 406 mm in diameter and features in-wheel suspension, reducing vibration and shock on the robot and video feeds. Slip-steering capabilities have also been improved with the design of a custom tread.

## WHEELS

Previous COLE models have rolled on injection-molded ABS garden cart wheels. These wheels offer little shock absorption and vibration attenuation, and require a significant amount of modification before they can be used on a robot. In response to these shortcomings, custom wheels have been manufactured out of laser-cut carbon fiber molded in a 3D-printed mold. The combination of using a laser cutter to cut the dry fibers and the complex geometry available from additive manufacturing allows for multifunction composite wheels that greatly improve the performance of the COLE robotic platform. Using the composite spokes as compression springs the wheels incorporate suspension into their lightweight design. Starting from a single spoke element, several stack ups were fabricated and tested. Next, a small wheel section (1/10th of a wheel) was tested to evaluate the effect of matched spoke pairs. Full wheels were fabricated in the 3D printed mold (See Testing section). See Figure 1 for the wheel and tread.

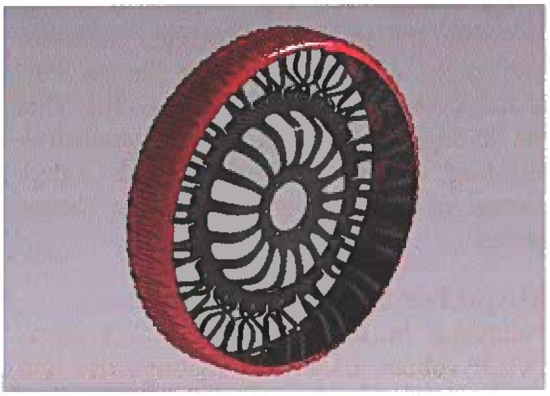

FIGURE 1: COMPLIANT COMPOSITE WHEEL WITH URETHANE TREAD

## TREAD

Extensive research was conducted on designing a tread for a slip steer robotics platform. The RoboUtes characterized a milled carbon-filled, Kevlar-reinforced urethane tread material. Tread for the wheels was designed for a reduction of axial loading on the robot during slip-steer conditions while maintaining sufficient traction in the direction of travel. The tread also needs to be symmetrical to allow for placement on any wheel of the robot. A detailed image of the tread geometry is below in Figure 2.

FIGURE 2: DETAIL VIEW OF THE TREAD GEOMETRY

## FIELD REPLACEABLE MOBILITY MODULE (FRMM)

Cole VI uses a modular approach to its mobility solution, containing the necessary electronic and mechanical elements in a single unit dubbed the Field Replaceable Mobility Module (FRMM).

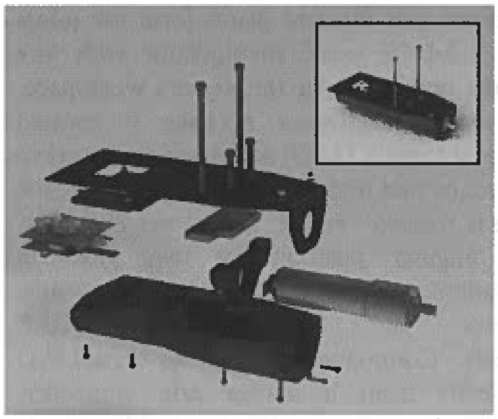

**FIGURE 3: EXPLODED VIEW OF THE FIELD REPLACEABLE MOBILITY MODULES.**

The FRMMs are interchangeable, with identical construction and a simple switch for wheel identification. The module contains a 24V DC Maxon gear motor which provides 9280 mNm of continuous torque and draws 4.2 Amps maximum continuous current. The motor shaft quadrature encoder has a resolution of 10 CPT, resulting in an output resolution of 1030 CPT after the 103:1 gearbox. Running at max voltage the flat ground cruising speed is 1.73 m/s. The throttle control is adjustable down to 1 mm/s for fine motor control during rock climbing events. Electronics and the motor mount to a right angle carbon fiber structural element (see Figure 3). Wheels attach with igus(™) slewing rings to isolate the motors from radial, transverse, and axial loading. The assembly is enclosed with a 3D printed shell that is reinforced with a spectra epoxy matrix for an abrasion resistant finish.

To facilitate complete modularity each FRMM contains all electronics required for operation on a single integrated custom PCB called a FRMM Electronics Module (FEM). The FEM consists of a Teensy 3.1 Microcontroller, Pololu Simple motor controller, nRF radio, and Pololu ACS711 current sensor. All commands are received and all data are returned via the nRF radio, such that the only physical connection to the chassis is via the power and ground wires. 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 directly attached 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

For a telerobotic system to be considered truly capable of exploring other worlds that system must have some way of 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. 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 significantly more advanced tasks.

COLE VI's manipulator is effectively made up of a 3-DOF serial manipulator for end effector positioning followed by a 2-DOF continuum 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 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). The manipulator is a standard elbow robot with three links. See Table 1 and Figure 4 for the Denavit-Hartenberg parameters.

TABLE 1: MANIPULATOR DENAVIT-HARTENBERG PARAMETERS

| i | $a_i$ | $d_i$ | $\alpha_i$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | $\pi/2$ | 16" | 0 | $\theta_1$ |
| 2 | 0 | 0 | 19.75" | $\theta_2$ |
| 3 | 0 | 0 | 18" | $\theta_3$ |

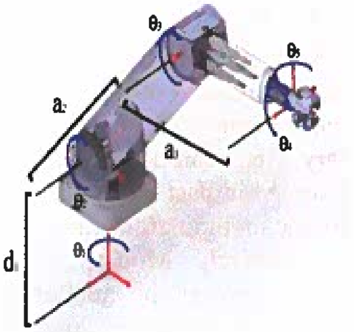

FIGURE 4: MANIPULATOR JOINT AND LINK ARRANGEMENT

The manipulator arm's structural components were cut from 6061-T6 aluminum using an OMAX Precision Abrasive Waterjet Cutting Machine. Bends were produced on a standard sheet metal brake, and drill and tap operations were performed on a vertical milling machine. Rotating connections are constructed using igus iglide slewing rings. Dimension, Lulzbot, and Solidoodle 3D printers were employed to create various 3D-printed components at their respective levels of cost and quality.

## UNIVERSAL ARM DRIVE UNIT

The Universal Arm Drive Unit (UAD) was developed to streamline the design, manufacture, and maintenance of the manipulator system. The UAD contains the necessary components to perform closed loop servo control on a rotary joint (see **Error! Reference source not found.**). The main unit of each UAD is the same for the turntable, shoulder, and elbow joints. Custom baseplate, humerus, and forearm plates form the joints into a 3-DOF serial manipulator with link lengths optimized for the desired workspace. A custom electronics package is located adjacent to each UAD, and manages the servo control of said joint. Angular velocity of each joint is tracked via two quadrature encoders, and angular position by two precision potentiometers- a 400% increase in arm sensors vs. all previous COLE models. Commands are sent to each UAD wirelessly from a master arm controller, allowing for the higher-level manipulator code to be developed independently from the lower-level joint code (see Figure 5).

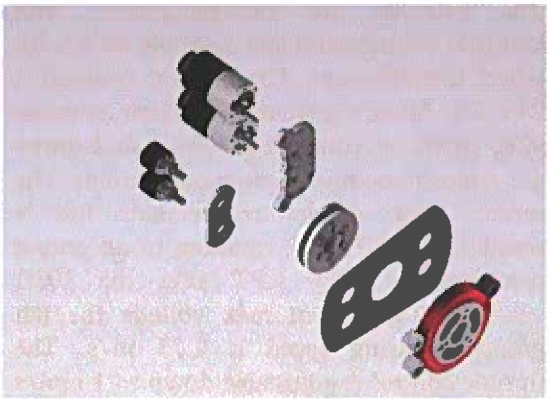

FIGURE 5: EXPLODED VIEW OF THE UNIVERSAL ARM DRIVE UNIT

TABLE 2: BILL OF MATERIAL FOR EACH UAD

| Bill of Materials | |
|---|---|
| Component | Retail Price |
| 131:1 37D Pololu Gearmotor | $25 |
| 64 CPR Quadrature Encoder | $15 |
| Bourns 3549 Linear Potentiometer | $18 |
| 32DP 20T Steel Drive Pinions | $3 |
| 32DP 20T ABS Potentiometer Pinions | $0.20 |
| 32DP 100T Delrin Driven Gear | $17 |
| IGUS iglide PRT Slewing Ring 02-20-AL | $24 |
| Custom PCB | $9 |
| Teensy3.1 | $20 |
| nRF | $1.50 |
| Pololu Dual Driver Motor Driver | $60 |

FIGURE 6: EXPLODED VIEW OF THE MODULAR WRIST ASSEMBLY

## WRIST

COLE VI features an evolution of the innovative wrist design from COLE V. Miniature linear actuators emulate the tendon action that drives a biological wrist and hand. The hand is joined to the forearm via a flexible accordion-style tubing that locates it axially, and prevents rotation about the axial line. Three linear actuators are connected to the hand via cables, which allow for transmission of both pushing and pulling forces to the hand. By commanding linear position combinations of the three actuators the operator can achieve a wide variety of wrist poses. The wrist is capable of approximately 70 degrees of extension/flexion, and 70 degrees of deviation. The actuators are Firgelli Technologies L12s, generously donated by Firgelli. Each actuator has its own integrated motor controller and position sensor, making them very simple to interact with (see Figure 6).

## GRIPPER

COLE's gripping system has been the subject of intense study, design, and revision. RoboUtes members Michael Bills and Aaron Wernerehl conducted an independent study under the University of Utah's Undergraduate Research Opportunities Program dedicated to optimizing a grasping device, and the result of that study has been integrated into COLE VI. This gripper features 5 fingers mounted to a common palm in a 2-3 arrangement to allow for both spherical and cylindrical grasps (see Figure 7). The palm is made of 3D printed plastic, and features an embedded camera for use in aligning the hand with a target. The fingers feature 3D printed "bones" overmolded with a low-durometer silicone rubber "flesh." This composite approach allows for fingers that resist bending and torsion in undesirable directions, but offer little resistance against opening and closing along their intended paths. The fingers are tied back to a multiple linear actuators through load balancers, which allows for complex gripping patterns.

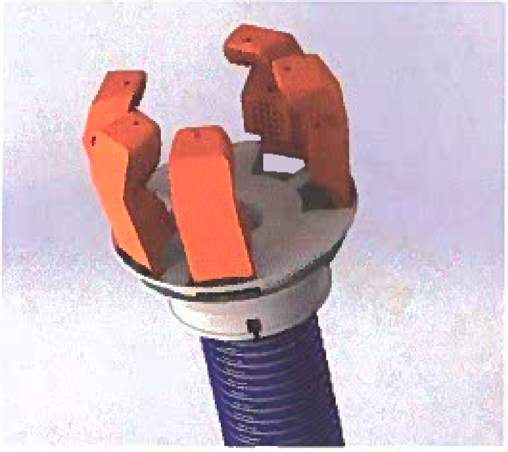

FIGURE 7: DETAIL VIEW OF THE END EFFECTOR

## MANIPULATOR CONTROL SYSTEM AND PATH PLANNING

The manipulator arm is functionally made up of two substructures; a 3 DOF elbow robot for spatial positioning, and a 2 DOF semi-spherical wrist for spatial orientation. During normal grasping operations the operator gives commands in an x-y-z space, and inverse kinematics equations are used to direct the end effector to that coordinate. The wrist uses accelerometer data to calculate the gravity vector, and orients itself normal to it. This control scheme greatly simplifies the task of the operator compared to previous arm control schemes, and allows the use of a very intuitive controller layout.

Manipulator arm automation has proved extremely valuable in past competitions, and has been greatly expanded and improved for 2015. COLE VI uses a Random Rapidly Expanding Trees (RRT) motion planner to deploy the arm into the workspace near the rock sample of interest. Grasp is performed manually, and control is handed back over to the RRT for rock return, and re-stowing. The RRT always selects safe paths, and typically selects paths that are quite close to the optimally efficient path. Minimizing the user-controlled portion of the grasping sequence is key to improving sample collection speed, especially when high latency is an issue. A more detailed report on the functionality of the RRT motion planner can be viewed in Appendix 2.

## VISION SYSTEM

Vision has continually proven to be a challenge in telepresent robotic systems. To overcome these challenges COLE VI uses the Axis Communications F44 vision system. 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 a RESTful API through which mission control can initiate feeds and set streaming parameters. Several 1080p-capable sensors are available for F44 compatible cameras and COLE VI has two cameras with 113 degree FOV and two with 194 degree FOV. The F44 system can be seen in Figure 8.

FIGURE 8: THE AXIS F44 REMOTE VIDEO SOLUTION

## VISION MODULE

The RoboUtes have developed a vision module including an Axis F-series camera and a LidarLite laser rangefinder (See Figure 9). The module allows for either the 194 degree or 113 degree FOV cameras. The distance measurement from the LidarLite is overlaid on the video feed at mission control and can be toggled by the robot operators. The vision module has a simple mounting system that can be easily installed anywhere on the robot, allowing for the vision system to be reconfigured without major redesign or remanufacture of the robot

FIGURE 9: EXPLODED VIEW OF THE VISION MODULE

### PAN TILT

The utility of a pan-tilt (PT) camera system used in conjunction with a head-mounted display (HMD) was proven on COLE V, and has been updated for inclusion on COLE VI. An Oculus Rift DKII headset and an actuated Vision Module are used to create telepresent awareness for the operator. Accelerometer and gyroscope data from the Oculus Rift are used to generate pan and tilt commands for the PT system, such that it follows the orientation of the user's head. The camera feeds are projected on the Oculus' displays, creating a very convincing telepresence experience. A barrel distortion shader is applied to the incoming camera feed to give the video feed the proper 'shape' to be effective inside of a HMD (see Figure 10)

FIGURE 10: AN EXAMPLE OF BARREL DISTORTION AND COLOR CORRECTION FOR A HEAD MOUNTED DISPLAY

### ARM CAMERAS

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 using the palm camera, a small endoscope embedded in the robot's 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 SYSTEMS

### BATTERY

The power system on COLE VI 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, 8Ah LiPo battery will be used allowing for 1.2 hours of run time and providing the appropriate voltage to the drive system.

### POWER DISTRIBUTION

All previous rovers in the COLE family have utilized passive power distribution, with an externally protected battery connected directly to subsystems via a power bus. While effective and simple to implement, these previous versions were unable to monitor the state of charge of the battery, leaving mission control literally in the dark when power ran out. COLE VI's power system (see Figure 11) is designed for use with unprotected battery packs and incorporates onboard battery monitoring, allowing the rover to continually update mission control with the status of its battery.

Pack monitoring is voltage-based, and implemented at the cell level. As the battery is discharged the cell voltage falls from 4.2V to 3.15V, at which point the power system automatically disables the manipulator and mobility systems to prevent battery damage. Unlike previous COLE rovers with external battery protection, the COLE VI power system leaves the computer and communications systems online to preserve contact with mission control. Additionally, if completing an objective is deemed worthy of risking battery damage the failsafe can be overridden and power restored to all systems. An additional benefit of this "soft-failsafe" is the ability to individually reset subsystems. In the event of a malfunction, any subsystem can be power cycled independent of all the other systems on the rover and hopefully restored to functionality.

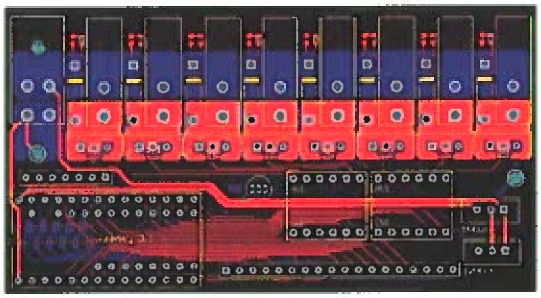

FIGURE 11: PCB LAYOUT FOR THE INTELLIGENT POWER DISTRIBUTION SYSTEM

## CONTROL AND COMMUNICATIONS SYSTEM

### NUC RUNNING 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 12 for an image of the Intel NUC.

FIGURE 12: INTEL NEXT UNIT OF COMPUTING

### NETWORK ARCHITECTURE

COLE VI uses a multi-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 13 for communication flowchart). 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, donated by T-Mobile.

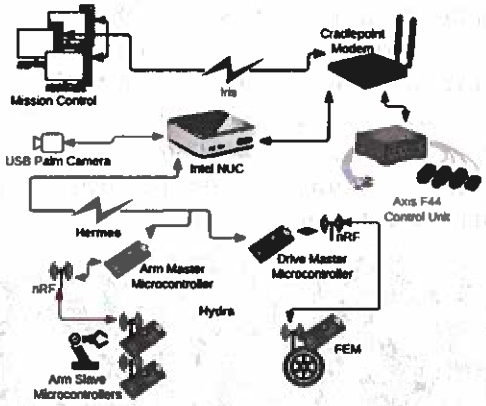

FIGURE 13: NETWORK ARCHITECTURE FLOWCHART

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 (see Figure 14). 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. Having 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 string-based key/value pair communication with the embedded controllers, and handles acknowledgements, negative acknowledgments, and retransmits as required to ensure steady wireless data flow.

FIGURE 14: GRAPHICAL USER INTERFACE FOR THE ROVER ONBOARD COMPUTER SOFTWARE

## 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 GRAPHIC USER INTERFACES

Controlling a complicated system like COLE VI 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.

Logistics - the Logistics Terminal requires two operators, and is used to both locate rocks and direct the driver to them. One of the operators is actively searching for rocks using an Oculus Rift DK2 connected to a pan-tilt camera on the robot. When a rock is spotted, pressing the spacebar causes a map to appear in the Oculus. By maneuvering the cursor over where the rock was spotted and clicking, the operator can place a "waypoint" that will display on a larger map in the logistics GUI outside of the Oculus. At this point, the secondary logistics officer can use this map, as well as the robot's telemetry, to direct the driver to the rock while the primary logistics operator goes back to searching for rocks (see Figure 15).

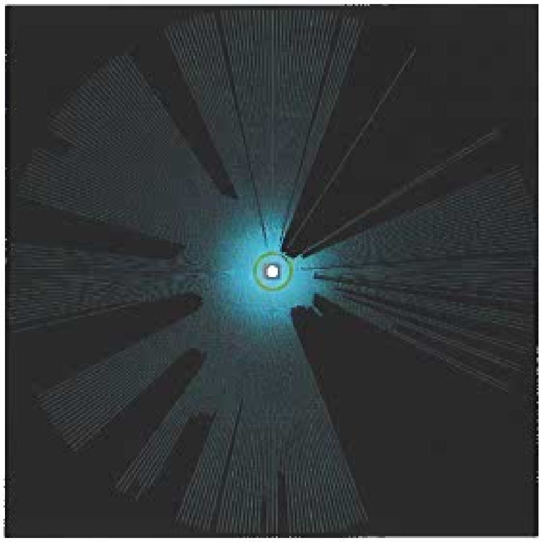

FIGURE 15: EXAMPLE DISPLAY OF LIDAR OUTPUT

Drive & Arm - the Drive and Arm Terminals deliver their users all of the necessary data to control their namesakes through a joystick (see Figure 16). 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.

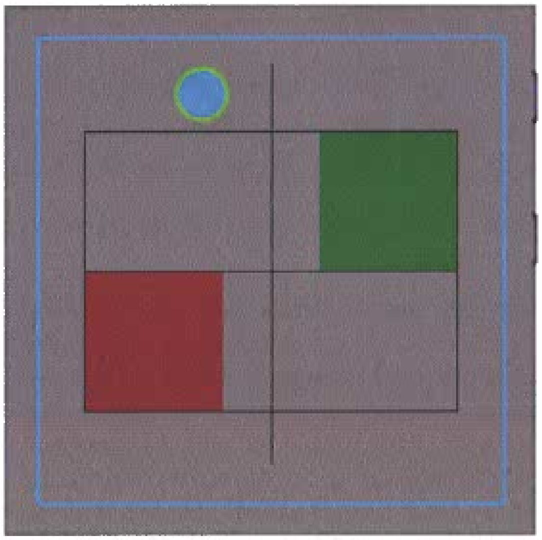

FIGURE 16: JOYSTICK FEEDBACK DISPLAY

# TESTING STRATEGY

## MATHEMATICAL AND SOFTWARE SIMULATION

Brainstorming meetings are held in RoboUtes Headquarters to discuss possible robot ideas.

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 SolidWorks FEA simulation. For a computer program, this might be a bandwidth test. The composite wheel will be used as an example throughout the testing portion of this report. Initial designs of the wheel were run through static loading simulation to determine if the idea was feasible (see Figure 17).

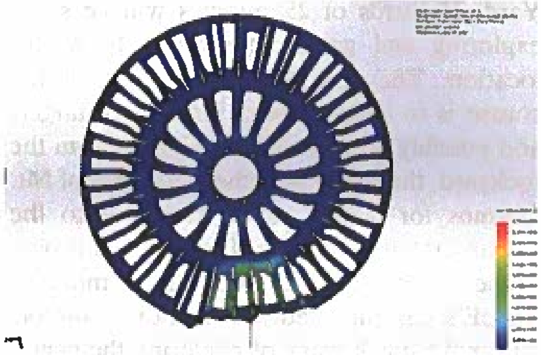

FIGURE 17: SOLIDWORKS FEA OF A CONCEPT COMPLIANT COMPOSITE WHEEL

## PROOF OF CONCEPT

Before any serious amount of time or money is invested in an idea, the RoboUtes typically manufacture a proof of concept prototype. This prototype is an approximation of the idea that allows for evaluation of the primary concerns. Prototypes can include 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. The composite wheel spokes were proof of concept tested to determine the required geometry and stackup to result in the desired compliance (see Figure 18 for spoke spring force testing results). Designs emerging from this stage result in much more thought-out final designs.

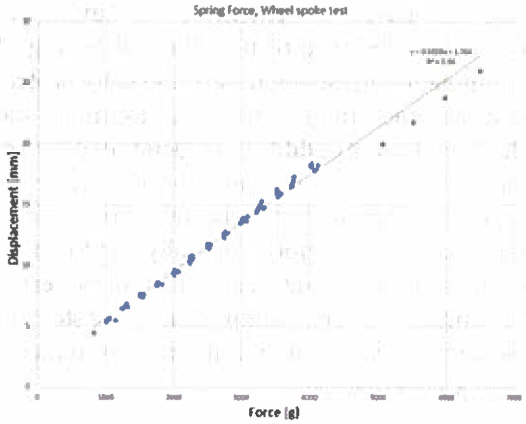

FIGURE 18: FORCE APPLIED TO SPOKE SAMPLE VS VERTICAL DISPLACEMENT

## 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. Bench testing also includes "stress testing" components and subsystems by letting them run continuously with a testing program. The increase in modularity of subsystems this year has increased the worth of prototype testing.

## 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. Once the vision system had been identified and cameras placed in modules, full system testing included trying out multiple camera positions for the best telepresent video feeds.

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. Consequently, the true potential of the platform has not been fully explored as each component and system cannot be tested to failure. Every component is tested to perform at least to its minimum requirements with a safety factor.

### TESTING RESULTS

COLE VI has been tested extensively in the University of Utah's Large Robotics lab. Full system tests have included driving and manipulating over a network via video feeds. Attending a large number of EPO activities has had the added benefit of rigorously testing our drive system at the hands of children. At full power COLE will climb almost any obstacle including rocks the size of its tires and inclines greater than 45 degrees. The results of the testing conducted are that COLE VI is a capable platform that is faster and much easier to control than previous COLE robots.

Testing and operator training will continue until the day before the competition.

## COMPETITION STRATEGY

### OVERALL PHILOSOPHY

The RoboUtes have observed that the most successful teams at Robo-Ops field highly mobile rovers, able to rapidly cover much of the course. With this in mind, the RoboUtes have constructed a very mobile robot, capable of traveling quickly to any area of the rock yard and successfully negotiating even the most difficult terrain. Covering the course quickly means a better chance at identifying and ultimately retrieving a large number of samples.

### THE GAME PLAN

A major robot weight reduction plan has been in effect during the 2015 RoboOps building season. By significantly reducing the weight of the competition robot, the RoboUtes will be able to compete at a later time slot. 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 VI will rapidly traverse to the Mars Rock Yard. Upwards of 25 minutes will be spent exploring and gathering samples from this location. The goal for this portion of the course is to collect several high-value targets and possibly an “Alien”. Moving on from the rockyard, the Rover will check the base of Mt. Cosmos for targets while relocating to the Lunar Craters. The time allocated to this next phase of course exploration is 15 minutes. COLE’s custom tread and fast drive motors will make quick work of exploring the center of the lunar craters followed by traversing the crater rims. Next the robot will move to the sand pit, and back up Mt. Cosmos. 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.

Upon discovering a rock sample, the pilot will use graphic overlays on the primary drive camera feed to position the sample to a fast and efficient sample collection location. The manipulator 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

The RoboUtes successfully obtained many project sponsors this year. This allows for a significant improvement in hardware from previous years. For example, the majority of the $4800 drive motors were donated by Maxon Motors. The team reached out for sponsorship on key components to improve the system while relying on the budget to purchase standard robot components such as motor controllers and raw materials. COLE VI sponsor donations totalled over $17,000.

The final value of the robot components is $10,912, which much of this being donated. Other project expenses include $2918 for competition and travel and $1700 for outreach. A final budget report will be compiled following the competition. Figure 19 provides a graphical breakdown of the robot expenditures.

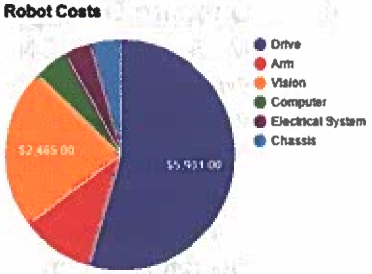

FIGURE 19: RELATIVE TOTAL COST OF VARIOUS ROBOT SYSTEMS

## EDUCATION AND PUBLIC OUTREACH

The RoboUtes place a heavy emphasis on educational and public outreach. RoboUtes members have donated more than 150 hours of outreach service during the 2014-2015 school year. RoboUtes events give the community an opportunity to interact directly with real-life robots, which helps to instill in young people an interest in science, technology, engineering, and mathematics.

Education and public outreach events have 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 helped host a Girl Scouts "Robots Rock" event. The scouts were able to drive COLE, manipulate the prototype sample acquisition system, and talk to the team about science and engineering. Additionally, the group has leveraged local TV news coverage of events to engage a much larger audience.

Outreach is not limited to University of Utah activities. The RoboUtes Facebook presence has been increased, now with 731 likes at time of submission. Ongoing sponsor outreach includes onsite meetings with sponsors, case studies, and sponsor specific videos showcasing the competitive edge provided by their products. The RoboUtes continue to engage and involve the community in the RASC-AL RoboOps competition.

# TECHINCAL SPECIFICATIONS

# RoboUtes

## COLE VI

### Telepresent Sample Acquisition System

COLE is a highly capable off-road exploration vehicle. Durability, speed, and precision are the primary objectives of this mobility system. This system is designed to explore an entire planet while collecting samples of interest.

## Specifications

### Physical Dimensions

| | |
|---|---|
| Mass | 30 kg |
| Length | 89 cm |
| Width | 73 cm |
| Wheel base | 50 cm |
| Height (stowed) | 45 cm |
| Wheel diameter | 41 cm |

### Drive

| | |
|---|---|
| Max Speed | 1.73 m/s |
| Maximum traversable obstacle | 25 cm |
| Motors: Maxon B72EEFDD9B01 | |
| Gear Reduction | 103:1 |
| Encoder resolution | 1030 cpt |

### Sample Acquisition System

| | |
|---|---|
| Degrees of freedom | 5 |
| Reach | 75 cm |
| Operating Area | 16,000 cm^2 |
| Rated Payload | 3 kg at 35 cm |
| Grip strength | 50 N |

### Power System

| | |
|---|---|
| Power Source | LiPo Battery |
| Battery Voltage | 24 V |
| Operating time | 1.2 hrs<br>8Ah Battery |
| Drive system power | 24 V |
| Sample Acquisition Power | 12 V |
| ROCS | 19 V |

### Rover Onboard Computer System (ROCS)

| | |
|---|---|
| Model: Intel NUC NUC5i5RYK | |
| Processor: Intel® Core™ i5-5250U | |
| Processor Speed | 1.6-2.7 GHz |
| RAM | 8 GB |
| Graphics: Intel HD Graphics 6000 | |
| Power Consumption | 15 W typ. |
| Operating System | Windows 8.1 |

### Connectivity

| | |
|---|---|
| Modem: Cradlepoint IBR 650 | |
| Antenna Gain | 2 DBi |
| T-Mobile 4G LTE Network Equipped | |
| Upload Speed | 4 MB/s typ. |
| Download Speed | 12 MB/s typ. |

# Real-Time RRT for Sample Collection in Mobile Robotics Applications

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David Van Ness
CS 6370 Computational Geometry and Motion Planning
University of Utah, May 2015

***Abstract*— It was hypothesized that the inclusion of a motion planning algorithm would improve the performance of a teleoperated sample acquisition/pick and place style robot. After reviewing the task, robot, and available motion planning techniques it was determined than an RRT (rapidly exploring random tree) algorithm would be the best fit for the specific problem formulation. A workspace was defined for the robot which defined the robot chassis as an obstacle, and all other locations as free space, with the option to add additional obstacles as desired. The RRT was performed in MATLAB. Valid paths were exported from MATLAB via TTL serial to the robot arm, which then executed the path. The robot was able to follow the paths generated, and successfully avoided collisions with the robot chassis, as well as other pre-programmed obstacles. It was determined that the performance could be further improved by porting the MATLAB side of the system into a compiled language like C++, and running the algorithm locally onboard the robot. The system was concluded to be a successful proof of concept, and future work will focus on improving the practical performance of the system.**

## I. INTRODUCTION

Many of the major problems of robot control have been declared 'solved' over the last three decades, with huge advancements in computer engineering and electromechanical components making it possible to build and control extremely robust robotic systems in real time. Unfortunately many of these advancements require a set of idealized conditions to be provided: unlimited mass, unlimited power, unlimited computing power, unlimited knowledge of the environment, unlimited budget, etc. These are fair assumptions to make in an industrial automation setting, but mobile robots operating in unstructured environments do not have any of these luxuries at their disposal, and more research is required to ensure that these type of robots can meet performance requirements imposed on them. This paper explores implementing an advanced motion planning algorithm on a low mass, low cost mobile robot representative of the robots currently working in planetary exploration, search and rescue, facility patrol & inspection, and other similar tasks. First, the background and context of the task, robot, and algorithm will be presented for the reader's reference. Next, the chosen approach to the motion planning problem will be discussed. The experimental results of the method will be presented, along with some discussion of their implications. The paper concludes with an evaluation of the performance of the overall system, and a discussion of the future work to be performed.

## II. BACKGROUND AND CONTEXT

### *A. The Task*

RASC-AL Exploration Robo-Ops is an annual robotics competition hosted by the National Institute of Aerospace (NIA) and National Aeronautics and Space Administration (NASA). Teams selected to compete must design, build, and deliver a robotic planetary exploration system to the Mars Analogue Field at NASA's Johnson Space Center (see Figure 1). The robots must be controlled remotely from the team's home university, using a civilian internet connection as the only means for sending commands to and receiving sensor data from the robot. The robot's primary objective is to collect as many designated rock samples as possible during a 1 hour period. The competition takes place in an unstructured environment with a number of obstacles and hazards present, and as such robots must use caution when undertaking sample collection tasks. Limited bandwidth and high latency make it difficult to create immersive telepresence, which limits the effectiveness of direct remote control of the robot. Automation is an attractive solution for decreasing the time required to collect rock samples, as it allows the robot to move quickly, decisively, and safely with only minimal user input or bandwidth use.

**Figure 1: Mars Analogue Field at JSC**

### *B. The Robot*

The University of Utah's competition robot is known as the Cellular Operated Land Explorer (COLE). COLE consists primarily of a communications system, a computer, a mobility platform, and a sample acquisition arm. For the purposes of this paper it is sufficient to say that the communication and computational systems are not limiting factors in the design of the motion planner. The mobility platform places the manipulator within easy reach of samples, and beyond that mainly serves as an obstacle which the manipulator must avoid.

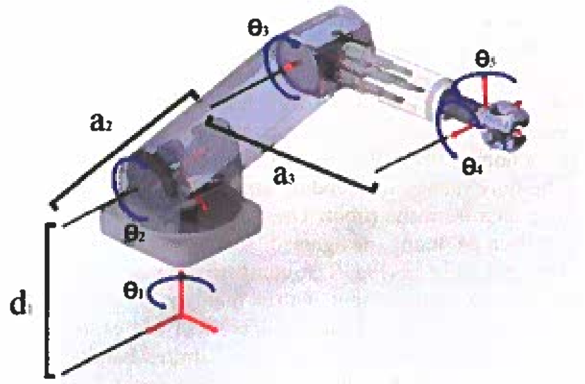

**Figure 2: D-H Diagram of COLE manipulator.**

The manipulator itself is a three degree of freedom (DOF) serial manipulator followed by a two DOF continuum wrist and an end effector. The purpose of the wrist is primarily to provide automatic leveling of the end effector, and as such motion planning was only performed for the first three serial degrees of freedom. The layout of the arm is typical of a "Shoulder Robot", where a planar pair-style two link manipulator is mounted perpendicular to a 'turntable' joint at some small offset. The Denavit Hartenberg parameters and diagram for the arm are shown in Figure 2 and Table 1.

**Table 1: DH Parameters of COLE manipulator.**

| i | $a_i$ | $d_i$ | $\alpha_i$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | π/2 | 16″ | 0 | $\theta_1$ |
| 2 | 0 | 0 | 19.75″ | $\theta_2$ |
| 3 | 0 | 0 | 18″ | $\theta_3$ |

### *C. RRT*

The rapidly exploring random tree (RRT) approach to motion planning was developed to resolve many of the issues encountered when applying traditional grid-based approaches to long, thin robots with multiple degrees of freedom. A small change of angle in a joint near the base of the robot results in a large displacement of the end of the robot. Grid approaches may miss collisions that happen near the end of the robot, unless the grid mesh is extremely fine. The RRT algorithm does not apply a mesh to the entire workspace, but instead allows a virtual version of the robot to explore the workspace, and only checks for collision along paths that the robot has indicated 'interest' in exploring. Extremely fine meshes can be applied along these paths to ensure that they are safe to traverse.
The algorithm itself is relatively simple:

1. A random sample configuration is selected. If that configuration is free (no collisions), continue.
2. Determine the nearest vertex to the random sample configuration.
3. Starting from the nearest vertex, apply a random control to the robot.
4. Use a physics model to simulate the effect of the random control over a given time period.
5. Check the control-generated final configuration and path for collisions, and save them to the vertices list if they are free.
6. Repeat until a vertex is discovered that is sufficiently close to the goal configuration.

The RRT search pattern tends to grow from its extrema, which gives its configuration-space graphs a very sparse, tree-like appearance. The RRT's reliance on a controls-based approach to exploring the virtual environment makes it exceptionally easy to apply to non-holonomic robots, or robotic arms. Because the paths are generated using the robot's real controls, the resulting motion plan consists of only movements the robot is capable of performing.

## III. APPROACH

A control system was implemented for a three DOF serial manipulator mounted to a mobility platform terminating in a two DOF continuum wrist. The geometry of the manipulator made self-collision impossible. Collisions between the manipulator links and the mobility platform were only possible if the end effector had also collided. This assumption permitted a simplification of the collision checking to just the position of the end effector relative to the mobility platform. The manipulator began in a known stowed position, which was provided to the RRT algorithm. The goal position was specified by either Cartesian coordinates in the workspace converted to joint angles by inverse kinematics, or by providing desired joint angles directly. The RRT began by selecting a random configuration of joint angles. Random configuration selection was biased toward the goal by selecting the goal configuration for 5% of samples. It proceeded by finding the nearest known safe configuration and generating a random control also composed of joint angles. Here, the key assumption that end effector position defines safe configurations was applied. Forward kinematics were used to determine the Cartesian coordinates of the end effector. If the z-coordinate of the end effector was above the highest point of the mobility platform, it was assumed to be in free space. Otherwise, end effector position was tested against a silhouette of the mobility platform (see Figure 3). Any non-colliding configuration was then added to the roadmap. This random sample, random control, collision check process was continued until the goal configuration was achieved. Dijkstra's Algorithm was used to determine the best path between start and goal configurations (Figure 4).

**Figure 3: Robot silhouette used for collision detection, with (left), and without (right), an additional obstacle in the workspace.**

Once the best path was found it was transmitted serially via radio to a microcontroller on the manipulator. Path locations were used by the microcontroller to continuously vary the set point of the proportional-integral control loop to achieve smooth manipulator motion between start and goal positions.

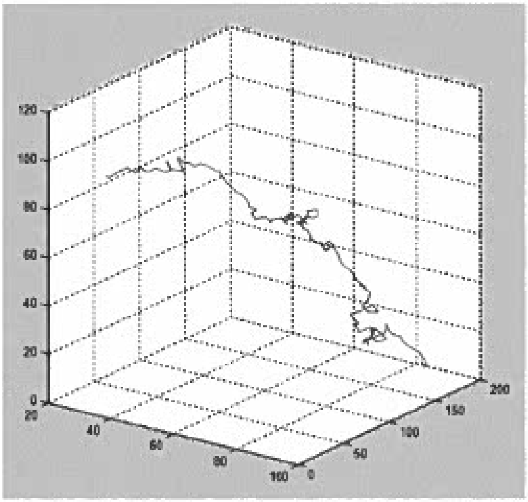

**Figure 4: A typical path returned from the RRT planner. The path is in configuration space, with the three robot joint axes plotted along the three axes.**

## IV. RESULTS

The RRT successfully determined collision free paths from any safe starting configuration to any safe end configuration. During testing there were no instances of failing to find a path. Transmission of the entire path to the microcontroller prior to executing any steps ensured safe operation in the teleoperation environment.

**Table 2: Path length and execution time**

| | Mean | Max | Min | Standard Deviation |
|---|---|---|---|---|
| Path Length (vertices) | 142.79 | 170 | 119 | 10.376 |
| Road Map (vertices) | 1942.1 | 3317 | 1283 | 374.2 |
| Computation Time (s) | 8.044 | 21.96 | 3.87 | 2.823 |
| Transmission Time (s) | 1.785 | 2.125 | 1.488 | 0.319 |
| Execution Time (s) | 3.57 | 4.25 | 2.975 | 0.638 |

The vast majority of planning time was spent on computing the RRT in MATLAB. The time required to transmit all path data to the microcontroller and time to execute the path depend directly on the length of the path (Table 2). At this stage of testing, path execution speed was artificially limited to protect the manipulator from itself.

## V. CONCLUSION

The RRT-generated paths were shown to eliminate the risk that the manipulator will collide with its own mobility platform or any detected obstacles. Transmitting the entire path prior to execution ensures the manipulator will follow a safe path. Latency in communication becomes a non-issue because the operator is not reacting to time-delayed feedback via video or other sensors. In the current implementation the motion of the robot is anecdotally slower using RRT than with an active human operator, but the improvements in manipulator safety are substantial.

Use of MATLAB to calculate the path is a substantial limiting factor. While useful as a development tool, the interpreted nature of the language increases computation time versus a compiled language like C++. The structure of the data is also inconvenient for communicating to microcontroller operating in a C++ environment.

To improve performance, all path calculation will be ported to C++. A more complete manipulator model will be developed to allow link collision detection with obstacles, removing the need for end effector only collision detection. Additional sensors will be integrated to detect the environment and dynamically update the collision model.

An important component of the RASC-AL Exploration Robo-Ops competition is the time limit. Future testing will include performance trials of the RRT against a human opponent teleoperating the manipulator.