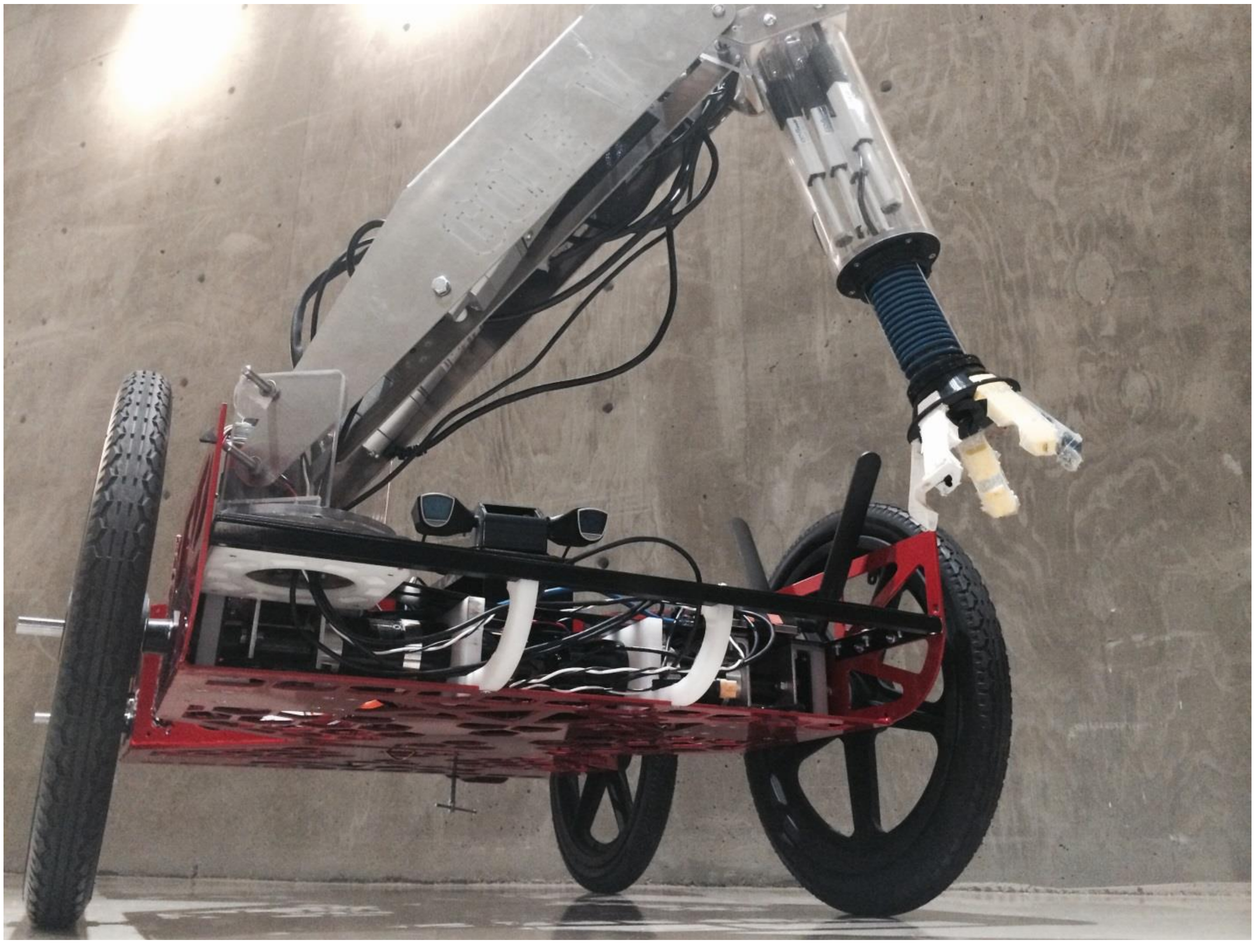

RoboUtes Final Technical Report for NASA RASC-AL Competition 2014

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Abstract. The University of Utah Student Robotics Club (The RoboUtes) will compete in the 2014 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. The 2013 RoboOps hardware has been kept in good working order, and is being used several times a month for Educational and Public Outreach (EPO) opportunities, as well as for testing and development. The RoboUtes are on schedule to compete at the Robo-Ops forum in June 2014, and anticipate being a force to be reckoned with on the competition field.

Figure 1: Final chassis, stowed configuration.

INTRODUCTION

A variant of the Cellular Operated Land Explorer (COLE) has competed at all three 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 2014 will be the debut of COLE mk V, 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. An expanded team roster and 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 the sample storage compartment, 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 and sample acquisition systems.

Figure 2: Final chassis, deployed configuration.

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 mk V's main system follows. See Appendix I: Technical Specifications for a quick-reference list of COLE's vital statistics.

Chassis Design and Drive System

Chassis

The COLE mk V chassis is a true unibody design, a fairly serious departure from the body-on-frame construction used on previous systems. The majority of the chassis was cut from 6061-T6 0.125" Aluminum sheet on an OMAX Precision Abrasive Waterjet Cutting Machine. This technique allowed for all hole placement and material removal to be handled in CAD/CAM, saving dozens of hours vs. manual machining, as well as realizing substantial improvements in accuracy. The chassis sections were TIG welded together, and then powdercoated for durability and attractiveness. Strategically placed 6061-T6 0.5" aluminum square tube provides additional rigidity to the chassis. Polycarbonate and other clear sheet plastics are used to enclose the chassis and protect against ingress of dust and moisture. See Figure 3.

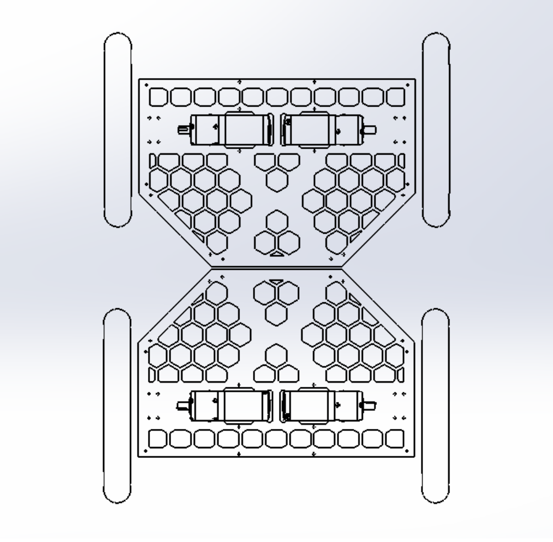


Figure 3: Chassis top view, with driveline

CSAS

COLE mk V features a passive roll joint between the two main axle sections, 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. A 2.5" diameter polycarbonate tube is used to locate the CSAS radially, while 2 high-performance thrust bearings and a clamping system provide axial location, as well as a resistance to bending (see Figure 4). These bearings provide a reduction in rolling friction and are lighter and smaller than previous spine incarnations.

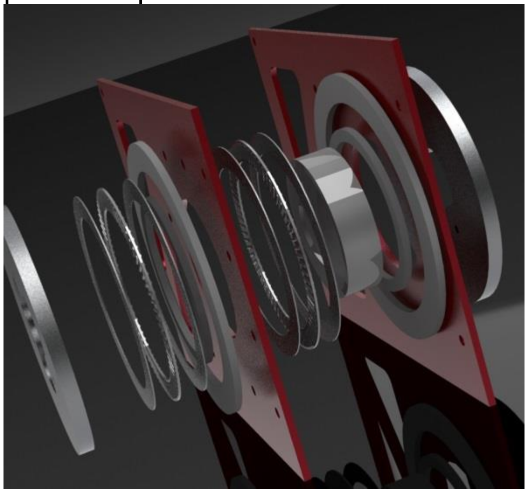


Figure 4: Spine assembly, detailed exploded view.

Wheels

COLE features 4, 16" diameter wheels, with pneumatic tires and a knobby, off-road style tread pattern. These wheels are custom-machined to mount to the axle assembly (see Figure 5). Pneumatic wheels are not necessarily optimal for planetary missions, but for the purposes of Robo-Ops they provide excellent traction, vibration damping, and durability. Foam-filled versions of the same units would be able to perform in any atmosphere (or lack thereof), and may be employed in future projects.

Figure 5: Wheel assembly, detailed exploded view.

Motors

Each wheel is actuated by its own dedicated 24V DC gear motor from Anaheim Automations (BDPG-60-110-24V-3000-R47) see Figure 6. With a peak torque of 29 Nm and a freerun speed of 64 RPM, these motors are both fast and powerful. Power consumption is approximately 50 watts at the speed/torque curve peak, but COLE generally operates below this point. The motors are coupled to an axle and bearing assembly to transmit power to the wheels.

Encoders

COLE mk V features U.S. Digital E3 Optical Encoders (see Figure 6) at each of its four wheels, generously donated by US Digital. The E3 is a ruggedized 1000 count-per-revolution, through-hole, quadrature encoder designed for hazardous environments. These encoders allow for precision position- and velocity-based closed loop control algorithms.

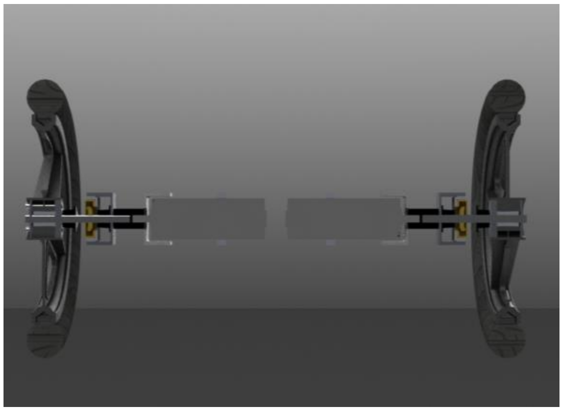


Figure 6: Drive chain, front cross section view.

Current Sensing

COLE also features Pololu ACS715 Hall Effect Current Sensors wired inline ahead of each motor controller. These allow the operator to see just how much “effort” the rover is putting into holding the desired closed-loop control command, allowing conditions like inclines, poor traction, or stalled motors to be easily diagnosed.

Control System

The drive system is controlled by Teensy 3.1 Microcontrollers. The Teensys communicate with the Rover’s Onboard Computer via USB, to 4 Pololu Simple High Power Motor Controllers over serial, 4 US Digital encoders via digital signals, and four Pololu Current Sensors via analog voltage signals (see Figure 7). The user generates commands for the left and right side motors independently using an XBox controller with dual analog sticks. The joystick commands and encoder signals are fed into a simple Proportional Integral Derivative (PID) closed loop controller in the Teensy, which returns an appropriate voltage duty cycle for the motor controllers to provide for the drive motors. Driving the rover is simple; driving both sides forward or backward will move the robot in that direction. Creating a speed differential between the two sides allows turning while moving. Running one side forward and the other in reverse allows the rover to turn in place. The closed-loop controller allows for the extremely precise, calculated movements that are key to aligning a rover with a rock sample of interest. PID also conveniently protects against undesired movements, like rolling down Mount Cosmos. A wiring diagram of this system has been provided in Appendix II.

Figure 7: Drive controller box, top view.

Manipulator Arm

For a telerobotic system to be considered truly capable of exploring other worlds, that system must have some way of physically interacting with the planetary environment. It has been demonstrated in past Robo-Ops forums that a very simple manipulator arm can collect rock samples effectively. However, modern planetary exploration has moved beyond the mission objective of “collect rocks," and as such the RoboUtes have elected to field a manipulator arm capable of completing significantly more advanced tasks.

Figure 8: Deployed manipulator arm, side view.

COLE mk V features an arm with 5 degrees of freedom, the specifics of each are discussed below. With a maximum reach of approximately 0.635 meters, the arm has an operating area of about 1.25 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). Figure 8 shows the basic profile of the arm, made transparent to show actuators.

Structure

The manipulator arm’s structural components were cut from various thicknesses of polycarbonate and 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 the vertical milling machine. Rotating connections are constructed using 0.25” stainless steel shaft, riding in bronze bushings where applicable. Dimension, Objet, and Solidoodle 3D printers were employed to create various 3D-printed components at their respective levels of cost and quality.

Turntable

The arm's yaw movement (x-y plane) is controlled by a Pololu 37D 121:1 12V DC gearmotor actuating a 70:11 spur-drive turntable, for a final drive ratio of 770:1. The steep gearing makes the turntable extremely powerful, and capable of making accurate, minute changes of angle for completing delicate tasks. Position data is acquired using a multi-turn potentiometer geared to the spur drive. The operator is able to issue commands with a precision of around half of a degree, yielding over 700 unique positions. The hardware is capable of approximately 355 degrees of rotation, but soft limits are set at 180 degrees to guard against collisions with other rover components. See Figure 8 for placement, Figure 9 for detail.

Figure 9: Manipulator arm turntable, detailed exploded view.

Shoulder

The arm's shoulder movement is controlled by a 12V DC linear actuator from Progressive Automation, with a 5 cm stroke. The actuator acts in a 3 bar assembly capable of realizing a minimum torque of 16 Nm, and a peak torque of over 30 Nm. The shoulder is capable of articulating approximately 15 degrees below horizontal and 45 degrees above horizontal, for a total freedom of around 60 degrees. Position sensing is accomplished via a multi-turn potentiometer. The angular position of the shoulder is a polynomial function of the linear position of the actuator, yielding a precision that varies between approximately 0.1 and 1.0 degrees. See Figure 8 for placement.

Elbow

The elbow's movement is controlled by a 12V DC linear actuator with a 10 cm stroke, assembled so as to achieve a similar degree of mechanical advantage as the shoulder actuator. The elbow has a maximum sweep of approximately 120 degrees. The linear position sensing of this sensor is less accurate, but the swept angle is much larger, a situation that results in the elbow having a similar degree of precision to the shoulder. See Figure 8 for placement.

Wrist

COLE mk V features an innovative new wrist design that uses miniature linear actuators to emulate the tendon action that drives a biological wrist (see Figure 10). 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.

Figure 10: Manipulator arm wrist, resting configuration.

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 mk V. 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 11). 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 single linear actuator through a load balancer, which allows the remaining fingers to keep closing after one or more fingers have become stalled against an object.

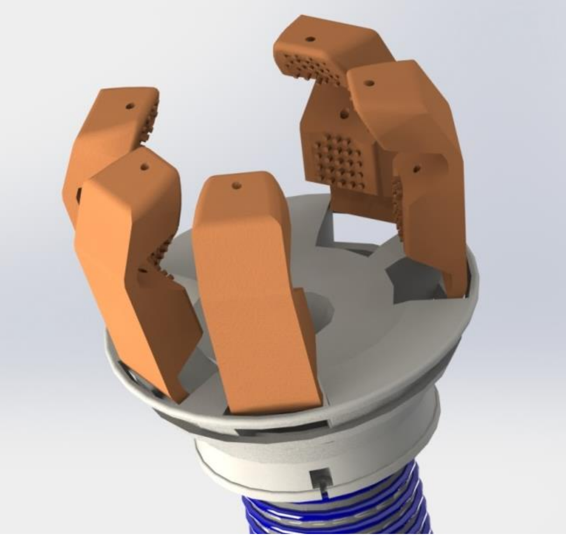


Figure 11: Manipulator arm hand, detailed view.

Control System

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. Each of these structures is controlled by its own Teensy 3.1 Microcontroller, with a dedicated USB communication cable. The "Arm Teensy" is augmented with 2 Pololu Dual Motor Drivers, for a total of 4 bidirectional motor channels(turntable, shoulder, elbow, spare, see Figure 12). The turntable, shoulder, and elbow motors and potentiometers are fed back to this controller, where the potentiometer data and operator's commands are fed into a Proportional-Integral (PI) servo controller to generate appropriate voltage levels for the motors. The "Wrist Teensy" sends commands to the 3 wrist actuators and 1 hand actuator via PWM signals, relying on the internal actuator controllers to handle motor and servo control tasks. The operator may control the arm using a variety of different control schemes, including simple joint control on an Xbox controller, inverse kinematic control on an Xbox controller, and macros for automating repetitive tasks. The GUI leaves the option open to add a kinetic telepresent controller at a later date as well.

A wiring diagram of this system has been provided in Appendix III.

Figure 12: Manipulator arm computer, top view.

Vision System

COLE uses a variety of separate camera systems to relay visual information from the field back to Mission Control. Several of these streams can be broadcast simultaneously over a strong 4G signal- the decision of which and how many streams to broadcast can be made at the discretion of Mission Control to suit current conditions and needs.

Pan Tilt Stereovision

RoboUte Matthew Monahan has been involved in research in cooperation with Oculus Rift to develop a pan-tilt stereoscopic 3D (PTS3D) camera system to be used in concert with an Oculus Rift headset to create telepresent awareness for an operator. COLE V features two Rocketfish Widescreen HD USB cameras mounted on a servo-drive custom pan-tilt array (see Figures 13 and 14). Accelerometer and gyroscope data from the Oculus Rift is used to generate pan and tilt commands for the PTS3D, 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.

Figure 13: PTS3D, close view.

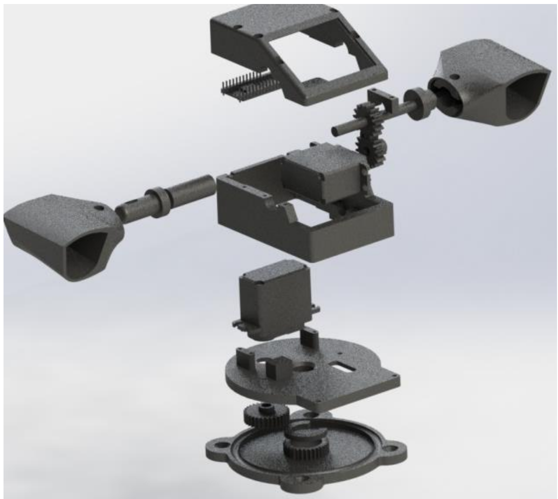


Figure 14: PTS3D, detailed exploded view.

Arm Cameras

The arm features two cameras for aiding in sample acquisition. A workspace camera is mounted to the humorous section of the arm, oriented such as to give a good 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.

Mast Cameras

COLE mk V features a deployable camera mast with 4 high-resolution Rocketfish webcams mounted forward, aft, left and right. These cameras are primarily used to take high-quality still images for locating rock samples or navigational hazards. These cameras are also often referenced to maintain a big-picture idea of COLE's placement in space, as they can be used to locate known navigational references in the environment such as buildings, mountains, the sun, etc, that are more difficult to discern on the high FPS, low quality video streams from other cameras.

The mast cameras are mounted on an actuated aluminum mast, capable of deploying them from a stowed position into a bird's eye (117 cm) view (see Figures 15 and 16).

Figure 15: Mast deploying mechanism, detail view.

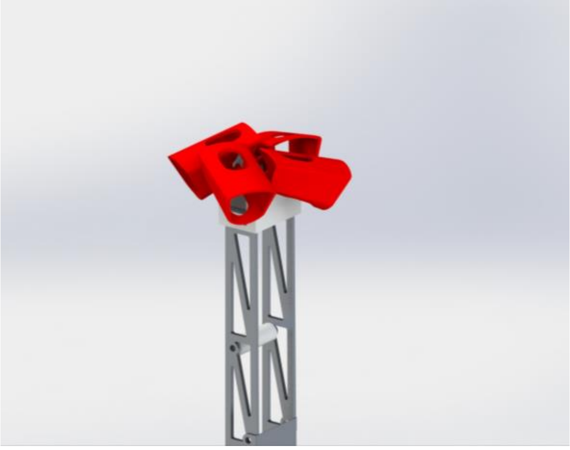


Figure 16: Mast camera cluster, close view.

Compression

COLE uses a customized RoboUtes variant of the MJPEG codec to compress and transmit video streams back to Mission Control. Initial efforts focused on UDP video streaming, but the number of lost video frames using this approach proved to be unacceptable. Standard TCP transmission eliminates the frame loss, but has a tendency to accumulate latency over time, especially on mobile connections. The RoboUtes codec is a compromise between these two techniques. In the event of a lost packet the sending side attempts to retransmit it, like any TCP application, but only if there is not already another frame ready to be sent. In the event that more than a second has passed and no new frame has been successfully sent, assuming frames are being requested, the entire socket is flushed in hopes that any hang-ups will be resolved.

Power Systems

Battery

COLE is equipped with a 24V 20AH lithium iron phosphate (LiFePo4) battery. Charging and discharging battery management circuitry is located on the battery to ensure safe operation at all times. This battery enables COLE to engage in high-speed "stunt roving" for several hours or slower, more introspective and scientific roving for much longer.

Voltage Regulation

Centrally located Mini-Box DCDC-USB high-efficiency programmable voltage buck-boost regulators provide clean 12 volt power for COLE's smaller actuators, fans, and other 12V components see Figure 17). Pololu Step-Down Voltage Regulators are dispersed throughout the rover to regulate the 12V line down to 5V for use in digital logic devices (i.e. encoders, motor controllers, current sensors, etc).

Figure 17: Voltage regulation cluster, detailed view.

The Rover's Onboard Computer (ROC) has its own internal Mini-Box ATX Power supply that supplies power in a variety of voltages to the various computer components. ROC's motherboard was specially selected for its ability to power a large number of USB devices, as COLE's microcontrollers, and cameras are all powered over USB.

Protection

A 50 amp resettable circuit breaker is wired in line with the battery and provides both normal and emergency shutoff capabilities. The LiFePo4 batteries are fitted with Anderson quick disconnects for safety and ease of installation. COLE's aluminum chassis has always been used as a ground plane for safety and convenience- COLE V's extensive use of powdercoating (an insulator) further reduces the risk of unintentional continuities. All power connections use polarized connectors, to prevent short circuits.

Control and Communications System

Rover's Onboard Computer

COLE mk V features a powerful onboard computer in order to process and stream multiple high quality video streams. The computer features an E3-1230Lv3 Zeon Server Processor, a GT210 Graphics Card, a GigaByte Ultradurable Mini ATX Motherboard, and 16 GB of RAM. These components were chosen not only for their power, but also for their power consumption- the entire system consumes less than 100 W of power at full load. The computer is housed in a custom enclosure featuring filtered, labyrinth-style fan inlets and outlets, and waterproof I/O cables (see Figure 18).

Figure 18: Rugged computer case, detailed view.

Network Architecture

All past COLE variants have communicated over the internet, but always via individual connections to privately hosted TELNET servers. These servers required significant effort and skill to connect to, and were extremely sensitive to changing IP addresses, signal loss, and high latency. COLE mk V, however, is a true World Wide Web device. As long as COLE is connected to the internet, COLE can connect to Mission Control's static IP, and teleoperation can be performed. COLE can access the internet via Wi-Fi, mobile broadband, or even a tethered smartphone in an emergency. The "first choice" network and hardware are described below, but an alternate modem/network combination that performs optimally in a certain region (i.e. Houston) could quickly be installed and used with relative ease.

Primary Modem

COLE's preferred connectivity device is a CradlePoint IBR650 Integrated Broadband Router, generously 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 RoboUtes HQ, a concrete dungeon located underneath the stately Kennecott Engineering Building.

Primary Connection

COLE communicates through AT&T's 4G LTE network. AT&T has generously granted the RoboUtes an unthrottled connection to their network, which will allow COLE to broadcast at full signal strength for the duration of the competition without any of the punitive throttling that is often applied to overzealous mobile data users. This connection averages 15 Mbit/s download and 7 Mbit/s upload in the Houston metropolitan area. Despite these high speeds, the connection may suffer from relatively high latency during the competition, given the geographical and network separation between Salt Lake City and Houston. All of COLE's systems have been designed from the ground up to require low bandwidth, and tolerate high latency without behaving erratically.

Mission Control Graphic User Interfaces

Controlling a system as complicated as COLE mk V is more than a single operator at a single computer can realistically do well. As such the Mission Control software has been broken into different terminals, with each terminal corresponding to a specific and manageable task. These terminals have been fully 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 manages inbound and outbound network traffic, making sure that the other terminals are communicating properly with COLE, and allocating bandwidth and priority as needed. The engineering terminal also monitors the rover's "vital statistics" such as processor heat, battery level, signal strength, etc. This terminal also has direct control over which and how many video streams are sent back to Mission Control and displayed, at any given moment.

- Logistics - the logistics terminal captures images from cameras mounted on various locations aboard COLE and allows the operator to comb over them in search of target rocks. Once a rock is found the user can mark its approximate location in mission control and the drive team can proceed to retrieve it.
- Drive - the drive terminal controls the motion of the rover's drive wheels via input from an XBox controller. Screenshots of this GUI have been included in Appendix IV.
- Arm - the arm terminal controls the motion of the rover's manipulator arm via input from an XBox controller. Screenshots of the competition and development arm GUIs have been included in Appendices V and VI, respectively.

TESTING STRATEGY

Mathematical and Software Simulation

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

Proof of Concept

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

Prototype Testing

Prototype testing involves a working model of the final product. This prototype is generally "bench tested," that is, tested in isolation from other components to ensure that it works well. Components may cycle through this stage many times, being designed and redesigned iteratively until the optimum solution is found.

Full Testing

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

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

Testing Results

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

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 and photographing a large portion of the course means a better chance at identifying and ultimately retrieving a large number of samples.

Redundancy/Diagnostic Capabilities

Historically faulty network connections and unpredicted runtime errors have plagued teams. For this reason a number of onboard diagnostic/repair routines have been implemented that should allow COLE to attempt to “fix itself.” Many of COLE’s systems are also equipped with the ability to report a large amount of status information. This diagnostic status information will become helpful in the event that the system is unable to rectify a problem on its own and the Mission Control team must resolve it manually.

The Game Plan

The RoboUtes team strategy will be somewhat dependent on the order of the competition. COLE mk V is a heavier robot than prior designs and will likely be seeded into an earlier start time. In the event that COLE is not the heaviest robot, the Mission Control team will review the competition streams of earlier teams and use this information as a reference prior to and during the RoboUtes competition run.

In all cases, the first action for COLE will be to raise the camera mast and obtain a high resolution panoramic overview of the competition grounds. The Mission Commander will use this information in concert with available maps of the site to determine the most effective route, keeping safety and the capabilities of COLE in mind.

A high level list of priority locations to visit will be rapidly compiled by the Mission Control team and will be followed unless an object of interest is spotted and a detour is ordered. Upon discovering a sample, 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 pride themselves on coming up with innovative and cost effective solutions to engineering problems. Whenever possible, the RoboUtes manufacture their own hardware, write their own software, and learn a lot in the process. A large portion of the raw materials that went into COLE MK V were donated, salvaged, or repurposed from other projects. Many people donated their time, materials, and expertise in making this project happen and the RoboUtes are grateful for those contributions. A full list of contributors can be found in Appendix VII.

Final budget numbers are still being compiled as the final testing phase may include additional expense and completion expenses are not yet finalized. Anticipated project expenses are estimated at $6900 for production, $3800 for competition and travel, and $1200 for outreach. A final budget report will be compiled following the competition. Figure 19 provides a graphical breakdown of the projected expenditures.

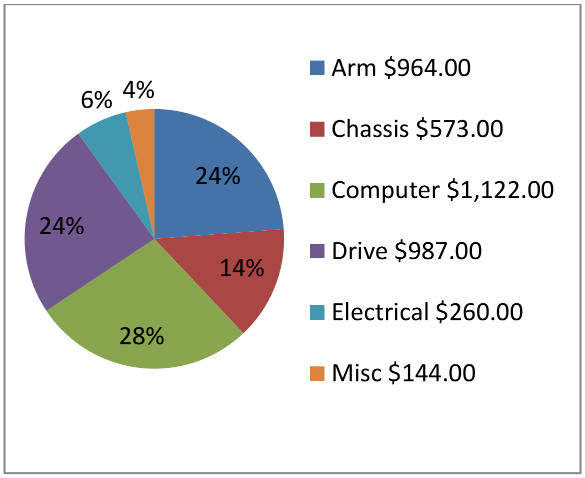


Figure 19: Budget Allocation

EDUCATION AND PUBLIC OUTREACH

Fostering interest in engineering is a primary objective of the RoboUtes. Various opportunities have been created for the RoboUtes to engage a diverse audience. The group visited a troop of Girl Scouts who were given insight to practicing engineering at a college level (see Figure 20). The scouts were able to drive COLE, manipulate the prototype sample acquisition system, and talk to the team about science and engineering. Other outreach opportunities included (but were not limited to) Engineering Day, See U at the U Day, Plazafest, and Mechanical Engineering Design Day. The last event featured COLE's youngest operator as a five-year-old successfully and enthusiastically maneuvered COLE around obstacles with a video game controller!

Outreach is not limited to University of Utah activities. The RoboUtes Facebook presence has been increased, now with 673 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.

Figure 20: RoboUtes participating in a January girl scout night.

Appendix I: Technical Specifications

Physical Dimensions		
Mass	43	kg
Length	100	cm
Width	73	cm
Wheelbase	58	cm
Height (Mast)	117	cm
Wheel Diameter	40	cm

Drive		
Rated Payload	40+	kg
Max Speed	1.25	m/s
Obstacle Size	0.25	m

Arm		
Degrees of Freedom	5	
Reach	0.635	m
Operating Area	1.25	m^2
Rated Payload	1	kg
Grip Strength	45	N

Power		
Chemistry	Lithium Iron Phosphate	
Battery Voltage	24	V
Battery Rating	20	Amp Hour
Minimum Operating Time	2	Hours
Typical Operating Time	4+	Hours
Voltages	5	V
	12	V
	24	V

Rover's Onboard Computer		
Processor	E3-1230Lv3	
Cores/Threads	4c/8t	
CPU Speed	1.8-2.5	GHz
RAM	16	GB
GPU	GT 210	
Power Consumption	<100	W

Communication		
Modem	Cradlepoint IBR650	
Max Up	50	Mb/s
Max Down	100	Mb/s
Network	AT&T 4G LTE	
Reported Up	7	Mb/s
Reported Down	15	Mb/s
Reported Latency	180	ms
Minimum Required Up	1.7	Mb/s
Minimum Required Down	0.3	Mb/s

Embedded Systems

Teensy 3.1		
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

Actuators

Drive Motors		
BDPG-60-110-24V-3000-R47		
Input Voltage	24	V
Rated Current	2.2	A
Stall Current	5	A
Rated Torque	4.71	Nm
Stall Torque	29	Nm
Rated Speed	64	RPM
Max Speed	53	RPM

Turntable

Pololu 37D 131:1		
Input Voltage	12	V
Stall Current	5	A
Stall Torque	1.76	Nm
Max Speed	80	RPM

Shoulder, Elbow

PA-14P-2-150		
Input Voltage	12	V
Stall Current	5	A
Stall Force	670	Nm
Max Speed	80	m/s

Wrist

Firgelli L12		
Input Voltage	12	V
Stall Current	130	mA
Stall Force	22.5	N
Max Speed	1	cm/s

Hand

Firgelli L12		
Input Voltage	12	V
Stall Current	150	mA
Stall Force	45	N
Max Speed	0.5	cm/s

Appendix II: Drive Wiring Diagram

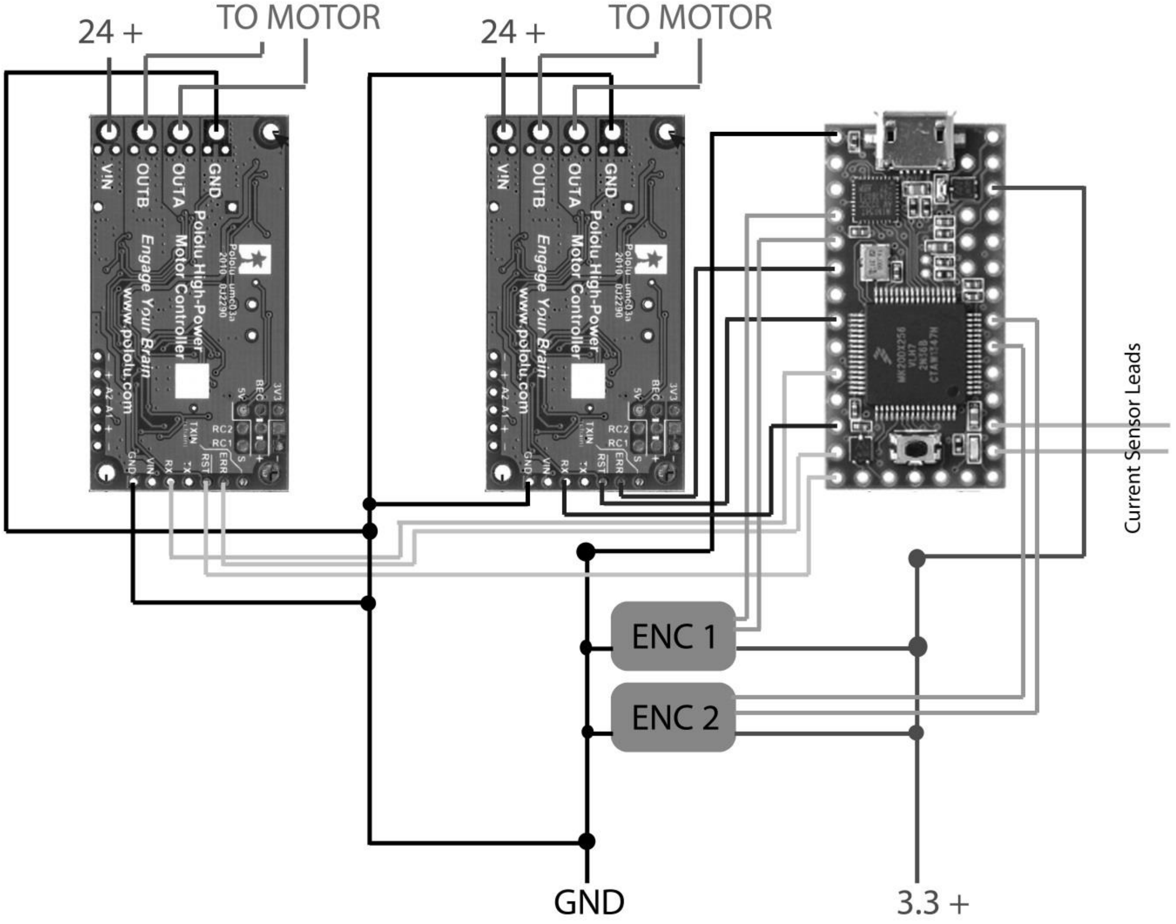


Figure 1: Wiring schematic of the drive embedded system. One Teensy microcontroller sends serial commands to two Pololu high voltage motor controllers.

Appendix III: Arm Wiring Diagram

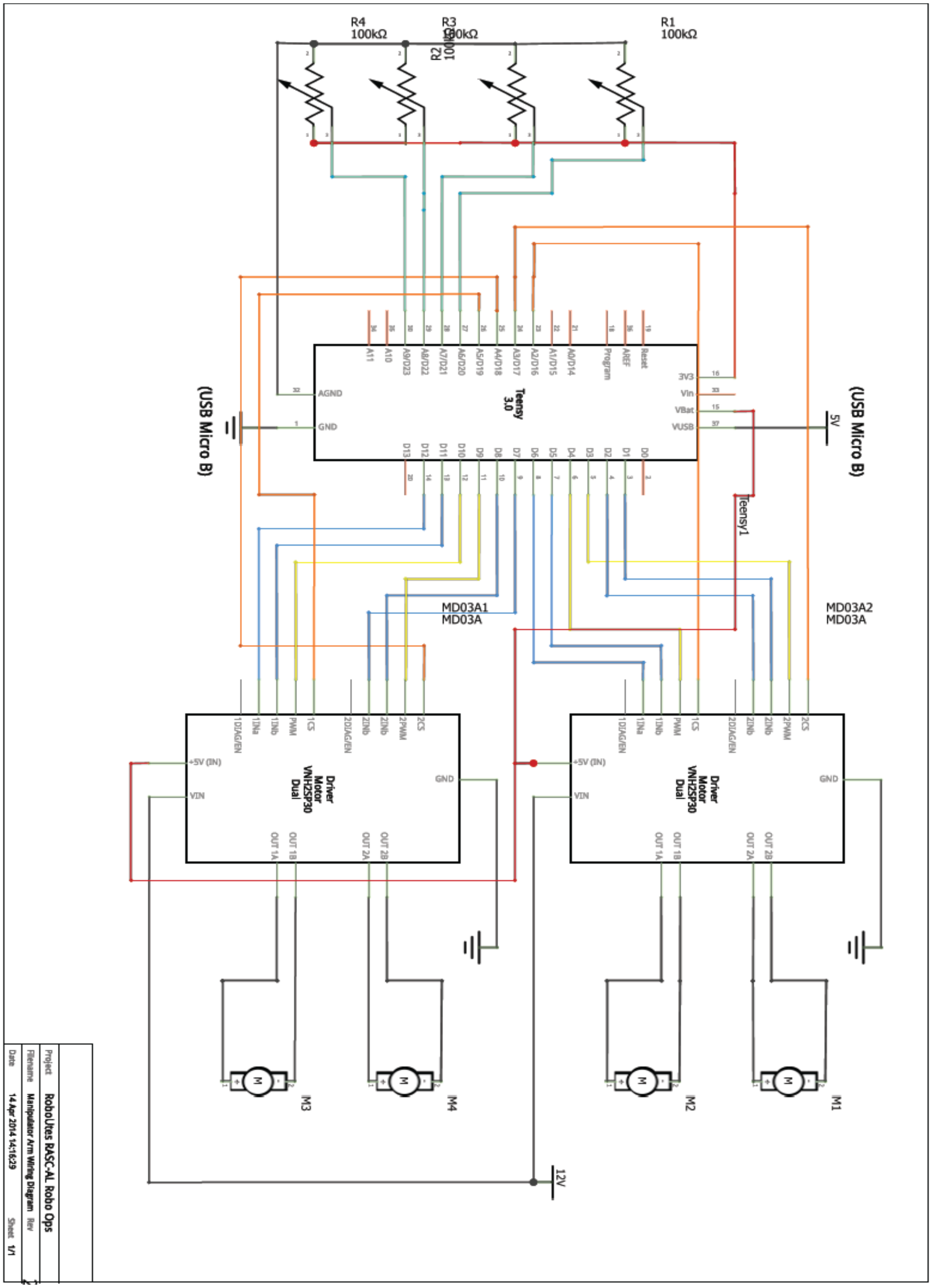
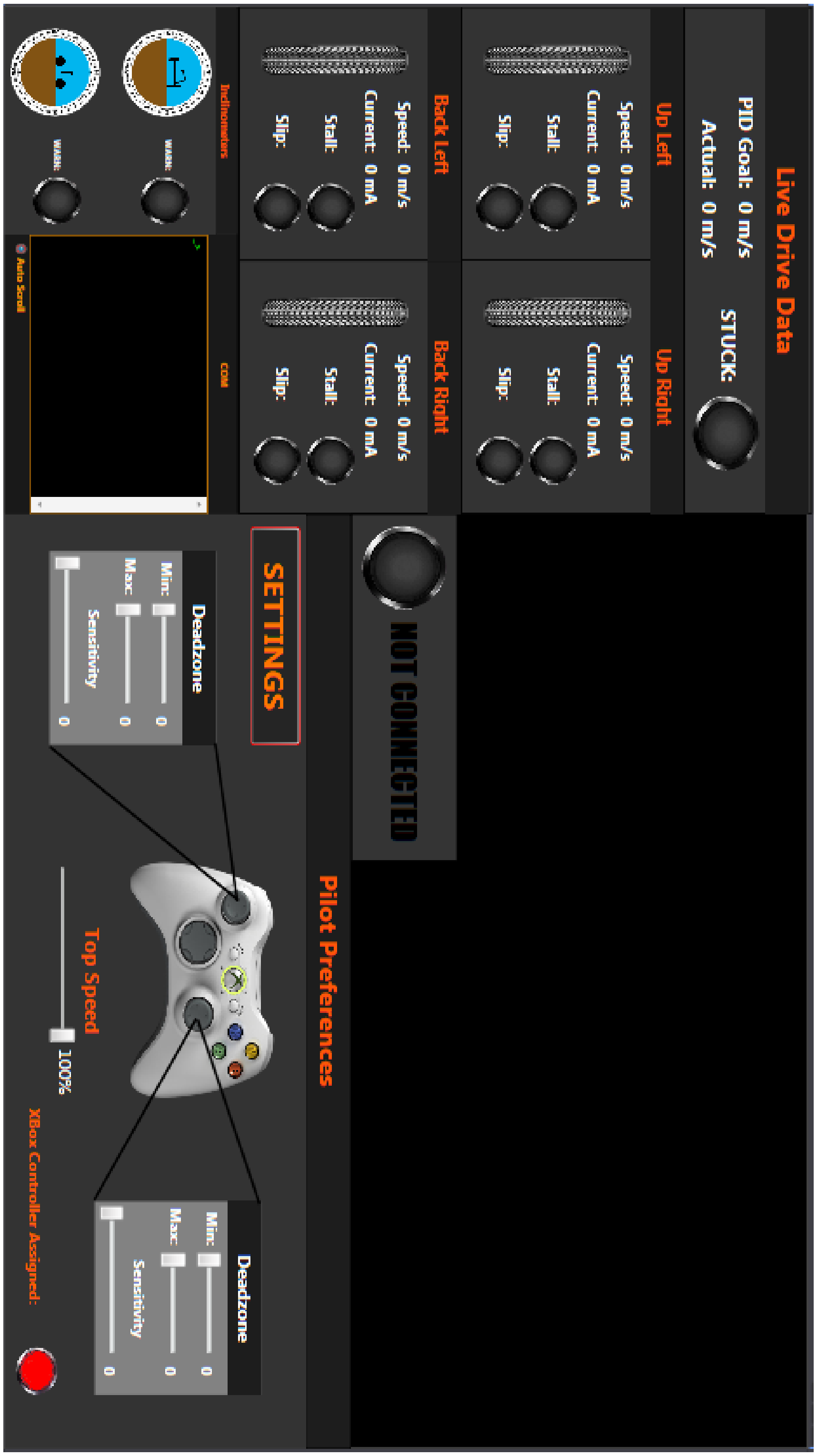


Figure 1: Wiring schematic of the arm embedded system. One Teensy sends serial commands to two Pololu duel motor drivers.

Appendix IV: Graphical Drive Terminal



PID Goal: 0 m/s
Actual: 0 m/s

Up Left
Speed: 0 m/s
Current: 0 mA

Up Right
Speed: 0 m/s
Current: 0 mA

Back Left
Speed: 0 m/s
Current: 0 mA

Back Right
Speed: 0 m/s
Current: 0 mA

Deadzone
Min: 0
Max: 0
Sensitivity 0

Top Speed 100%

Deadzone
Min: 0
Max: 0
Sensitivity 0

Figure 1: COLE mk V drive mission control software, integrates and displays various information pertinent to driving COLE, including current sensing of the various motors, pitch and roll sense, communication data, output controller data, and video feeds.

Appendix V: Graphical Arm Terminal

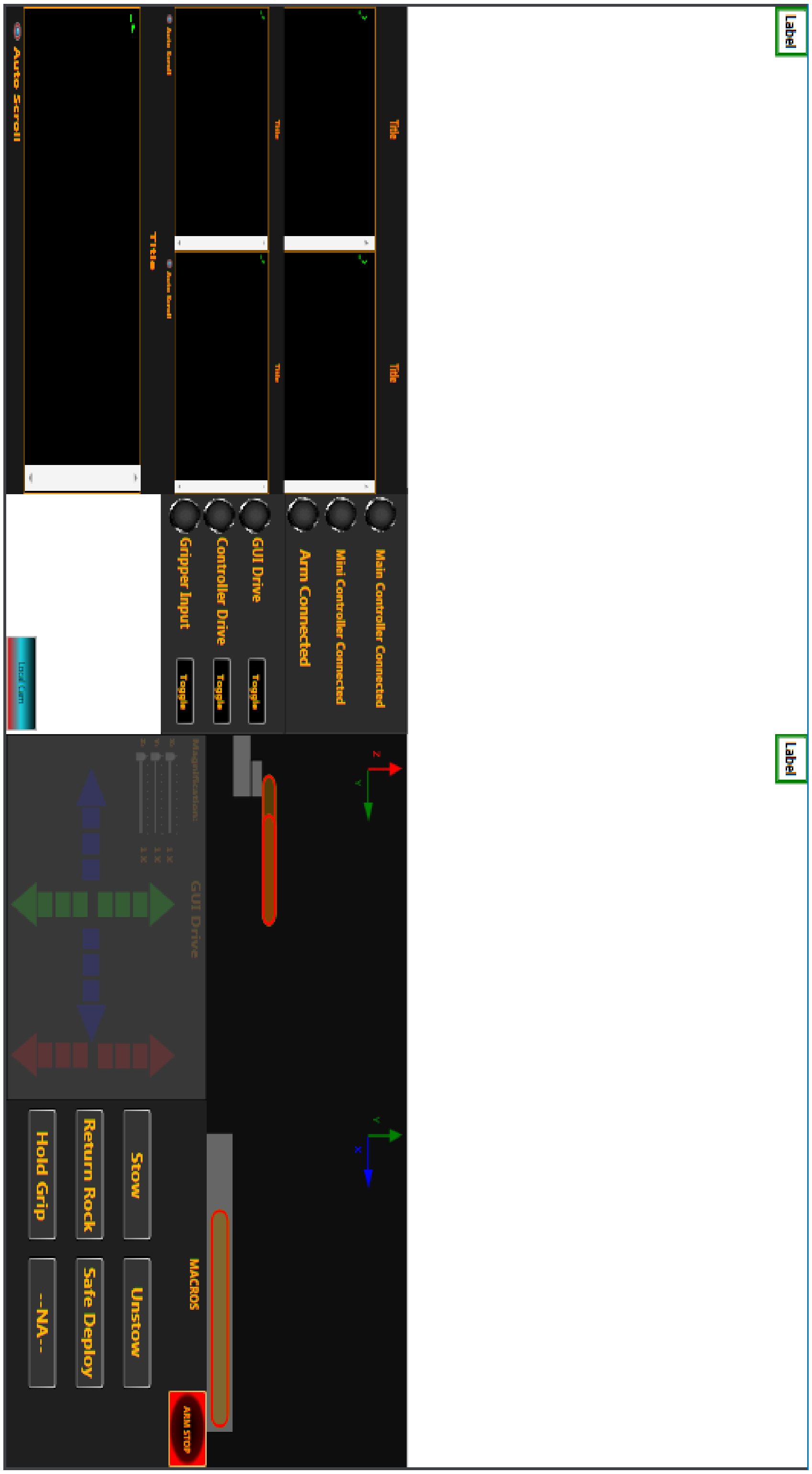
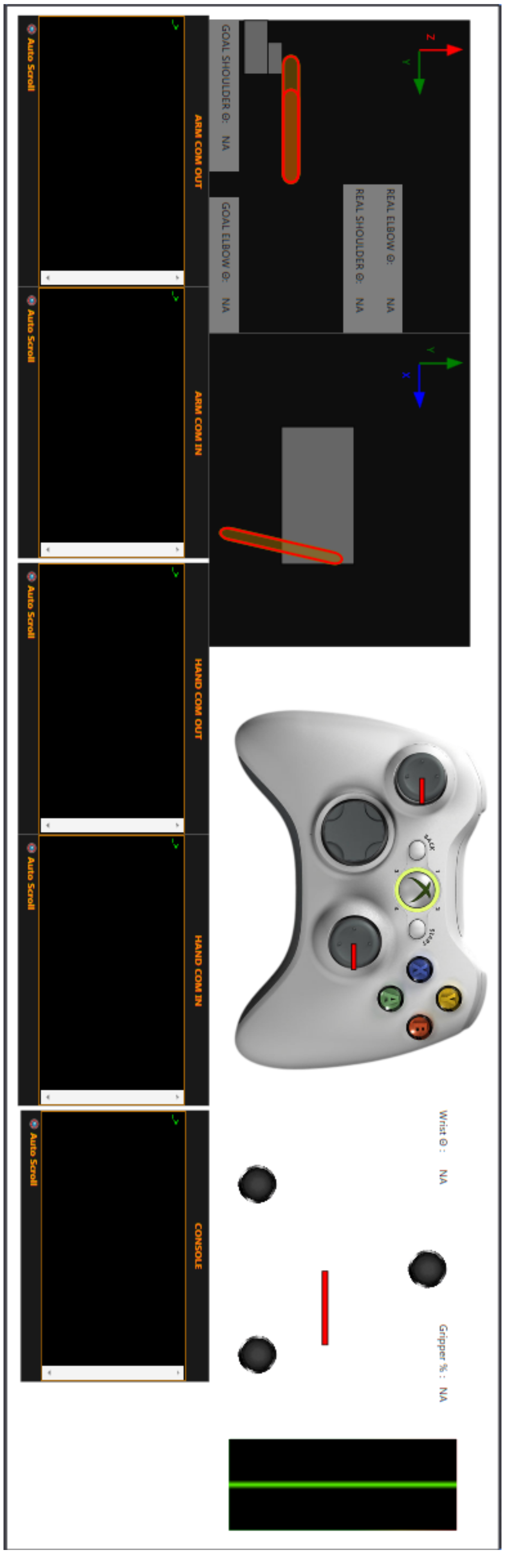


Figure 1: COLE mk V Manipulator arm mission control software, integrates and displays the current position of the arm, and relays the desired position of the arm from top and side views, communication channels, and video feeds.

Appendix VI: Arm Development Terminal



GOAL SHOULDER Θ: NA

GOAL ELBOW Θ: NA

REAL ELBOW Θ: NA

REAL SHOULDER Θ: NA

Wrist Θ : NA

Gripper % : NA

Figure 1: Development manipulator arm software, displays all communications, controller input, wrist control input, and gripper/hand control input.

Appendix VII: Sponsors

Figure 1: Back graphic for the RoboUte 2014 shirt, showing our sponsors.